BERKELEY LAB

EARTH & ENVIRONMENTAL SCIENCES

STRATEGIC VISION 2025

ACKNOWLEDGEMENT
The editors thank the many contributors to EESA Strategic Vision 2025. This work was conducted under the auspices of the Associate Lab Directorship of the Earth and Environmental Sciences Area, Lawrence Berkeley National Laboratory, which is managed by University of California for the U.S. Department of Energy under Contract No. DE-AC02-05CH11231.

HOW TO CITE
Earth and Environmental Sciences Area, Strategic Vision 2025, Lawrence Berkeley National Laboratory, Berkeley, CA. February 2017, pp.52. DOI: 10.2172/1344535

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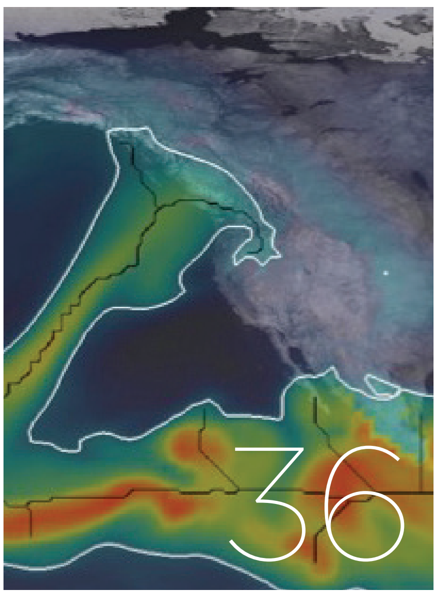

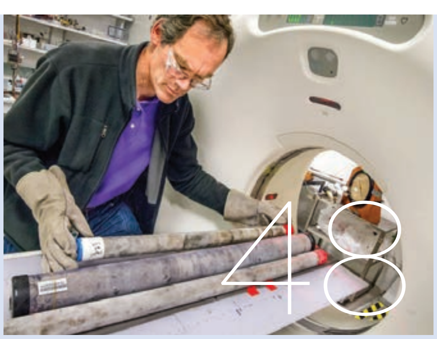

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VISION

A future where society can make informed decisions about the sustainable use of our planet's resources based on advanced scientific knowledge of the integrated Earth system.

MISSION

Advance and integrate diverse expertise to accelerate scientific discoveries and their translation into scalable solutions that sustain Earth's environment and the growing need for energy and water resources.

HARNESSING TRANSFORMATIVE RESEARCH TO PROTECT ENERGY AND ENVIRONMENTAL RESOURCES FOR CALIFORNIA, THE NATION AND THE WORLD

As the Associate Lab Director of Berkeley Lab's Earth and Environmental Sciences Area (EESA), I am proud to launch EESA 2025—a strategic research plan that reflects our Area's shared vision for the coming decade.

With this plan, we outline our research objectives and our collective vision on how EESA will contribute to solving the most pressing energy and environmental challenges of our time. Our strategic plan builds upon EESA resources and research that are already in motion, and articulates what we aspire to accomplish. The strategic plan aligns closely with U.S. Department of Energy's mission, and the developed solutions are expected to have great impact, nationally and globally.

Forty years after its creation, Berkeley Lab's Earth and Environmental Sciences has evolved into a mature research group of ~500 experts, which melds together multidisciplinary approaches to confront and solve urgent and complex Earth science challenges. EESA scientists use collaborative teamwork to discover the scientific underpinnings important for sustaining healthy soil and clean water, sequestering atmospheric carbon, using subsurface resources responsibly, and developing strategies for resilience in a changing world. This strategic plan seeks to harness innovative and diverse EESA talent to address five scientific Grand Challenges that collectively will lead to new approaches to protect and judiciously use our Earth's abundant resources.

EESA benefits enormously from being located in the collaborative and resource-rich San Francisco Bay Area innovation ecosystem, which includes world-class Department of Energy user facilities, the University of California at Berkeley, leading information and environmental technologists, and Berkeley Lab's own Biosciences, Energy Sciences, Energy Technologies, Physical Sciences, and Computing Sciences Areas. California, which is the world's sixth largest economy, offers a premier test bed for developing scientific solutions to optimize and sustain the environment, while satisfying growing needs for energy and water resources and other societal requirements.

EESA's organizational health depends on people who bring with them a diverse set of backgrounds and life experiences. We are fortunate to have a creative new generation of scientists join us in launching this plan. The expertise, creativity and passion of our scientists will continue to transform our understanding of Earth systems, and translate that understanding into a new class of environmental and subsurface energy solutions. It is an honor and a pleasure to lead EESA into this next decade.

Susan S. Hubbard

Susan S. Hubbard

Associate Lab Director,
Earth and Environmental Sciences Area

January 2017

EARTH & ENVIRONMENTAL SCIENCES

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A *NEW* PARADIGM FOR EARTH AND ENVIRONMENTAL SCIENCES

The scientific imperative of our time is to protect and use the Earth's abundant resources wisely to ensure healthy and prosperous societies for generations to come. Why the urgency? The answers are all around us. The planet is enduring record-breaking global temperatures, sea level rise, decrease in fresh water availability, and extreme storms, floods, droughts and fires. The increased frequency and intensity of these events have potential to disrupt economies and induce global-scale human migration. Natural cycles that sustain our energy, water and food are threatened—as is our health.

While some change is inevitable, unbridled change is not. There are ways to predict and influence how change unfolds to make both the natural world and human society more resilient. To do so requires a new and deeper understanding of Earth's complex processes. We must decipher and map the vast networks of these interconnected systems, the scale of which range from nanometers to thousands of kilometers, and from nanoseconds to centuries.

The EARTH SYSTEM is made up of interacting physical, chemical and biological processes (which include water, carbon, nitrogen, phosphorus and other natural cycles) in Earth's land, oceans and atmosphere, as well as all forms of life. In many cases, humans are now primary drivers of change in the Earth system.

To ensure water resiliency, for example, we must be able to predict emerging hydroclimate patterns that govern the future availability of water. We must then match these predictions with new approaches for storing water above or below ground, or treating unconventional water when and where fresh water is not naturally available.

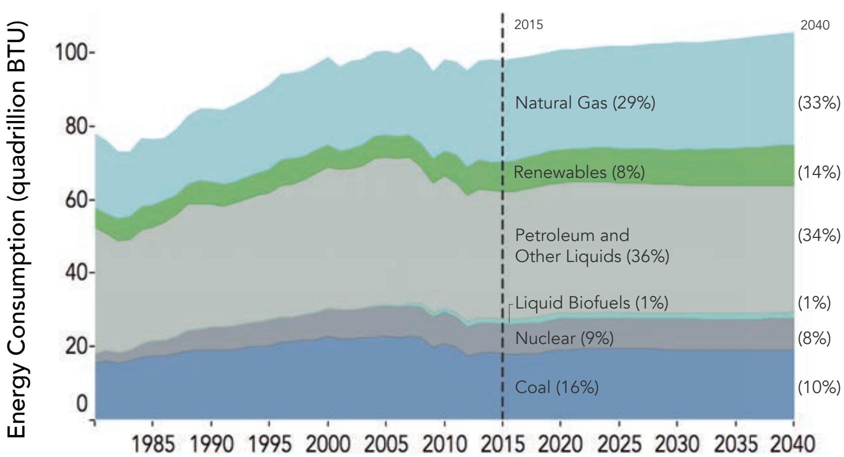
Learning more about the vast diversity of microbial life living beneath our feet will create opportunities to harness the microbes' metabolic activity to support everything from healthy soils and carbon storage to clean energy and novel bioproducts.

SCIENTIFIC RESEARCH IS PAVING THE WAY FOR LONG-TERM SOLUTIONS TO OUR INTERCONNECTED CLIMATE, ENERGY, AND ENVIRONMENTAL CHALLENGES.

Our smarter use of subsurface resources serves as an effective bridge to a clean energy future. We must develop natural gas, geothermal energy, and other resources while minimizing harm to our water, air and land. We must also be able to use the subsurface to store energy, water and CO_2.

This work has already begun. Research has revealed startling insights into the interactions of Earth systems, from deep reservoir systems to ecosystems to atmosphere. Earth scientists recognize the necessity of working together to connect and expand disciplinary boundaries to protect our connected world and develop innovative solutions for how we use its resources.

We face enormous challenges, to be sure. Nevertheless, we have an unprecedented opportunity to advance and integrate a new suite of tools and expertise required to understand Earth's complexity.



U.S. ENERGY OUTLOOK

Outlook for primary energy consumption by fuel source in the United States, a large fraction of which are derived from the subsurface. Generated using data from EIA Annual Energy Outlook 2016.

CALIFORNIA'S SUBSURFACE POTENTIAL

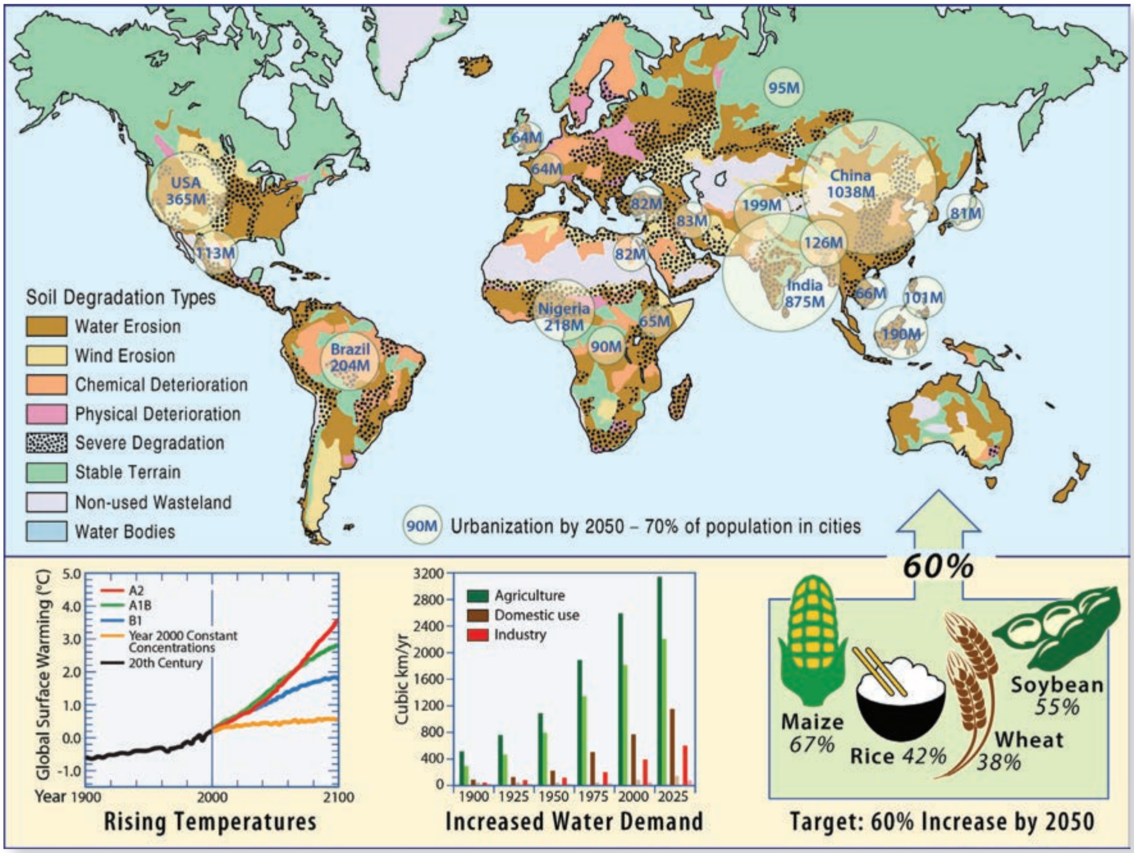
90 metric gigatons	CO_2 STORAGE
1.3 billion acre-feet	GROUNDWATER STORAGE
2.3 million acre-feet	WATER REUSE BY 2030

CA Department of Water Resources, Bulletin 118, 2003
CA Department of Water Resources, Water Reuse Potential in California, 2013
USGS Circular 1386, 2013

CALIFORNIA'S SUBSURFACE POTENTIAL

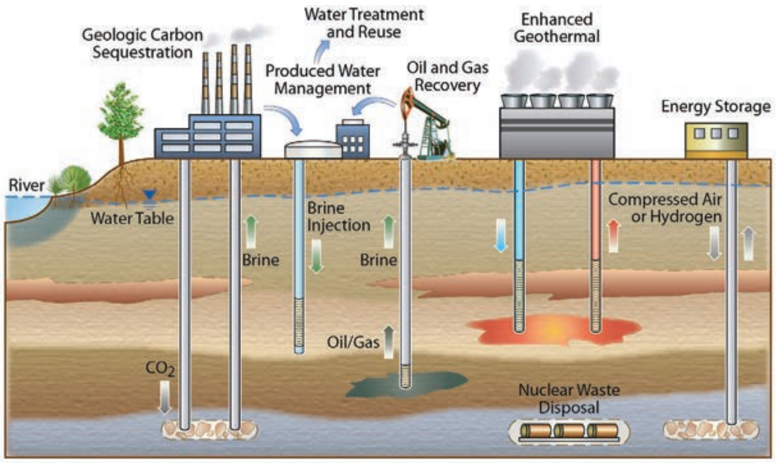
California's subsurface environment holds a high potential for storing captured CO_2 and groundwater, as well as increasing the fraction of water reuse from subsurface energy production.

The scientific imperative of our time is to protect and use the Earth's abundant resources wisely to ensure healthy and prosperous societies for generations to come.



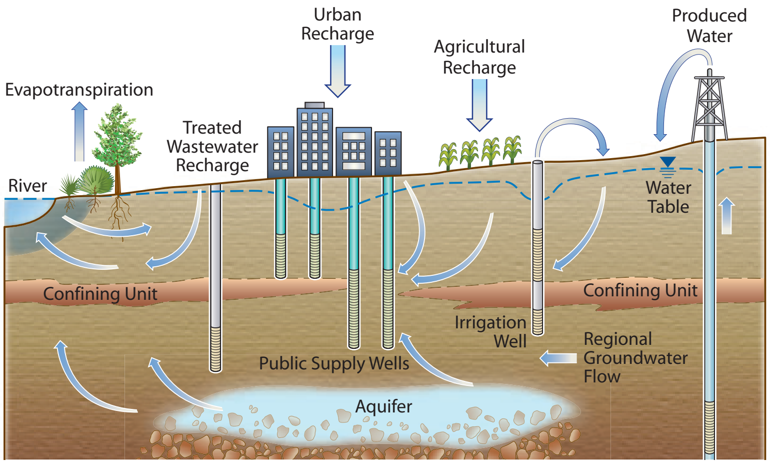
OUR CHANGING EARTH SYSTEM

Increases in population growth, urbanization, environmental degradation, and global climate change are presenting new energy and environmental challenges that science can help solve.



SUBSURFACE ENERGY AND STORAGE

Smarter use of subsurface resources offers an effective bridge to a clean energy future if we can develop natural gas, geothermal energy, and other resources with minimal impacts to our water, air and land surface resources, and if we can use the subsurface to store energy and energy waste.



GROUNDWATER MANAGEMENT

The complexity of coupled interactions in natural and intensively managed groundwater processes must be optimized for successful water management.

GRAND CHALLENGES

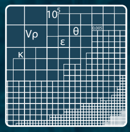
in Earth and Environmental Science

In the Earth & Environmental Sciences Area (EESA) at Lawrence Berkeley National Laboratory, or 'Berkeley Lab,' we have identified and taken on **FIVE AMBITIOUS, BUT ACHIEVABLE, EARTH AND ENVIRONMENTAL GRAND CHALLENGES.** These challenges embody our most urgent, high-priority research objectives for the coming decade, and represent opportunities to protect Earth's resources while using them wisely.

We also describe **THREE CROSS-CUTTING TECHNOLOGIES & PLATFORMS** that will enhance our capabilities to observe, understand and predict integrated Earth system processes over the range of spatial and temporal scales required by the Grand Challenges.

COMMUNITY OBSERVATORIES

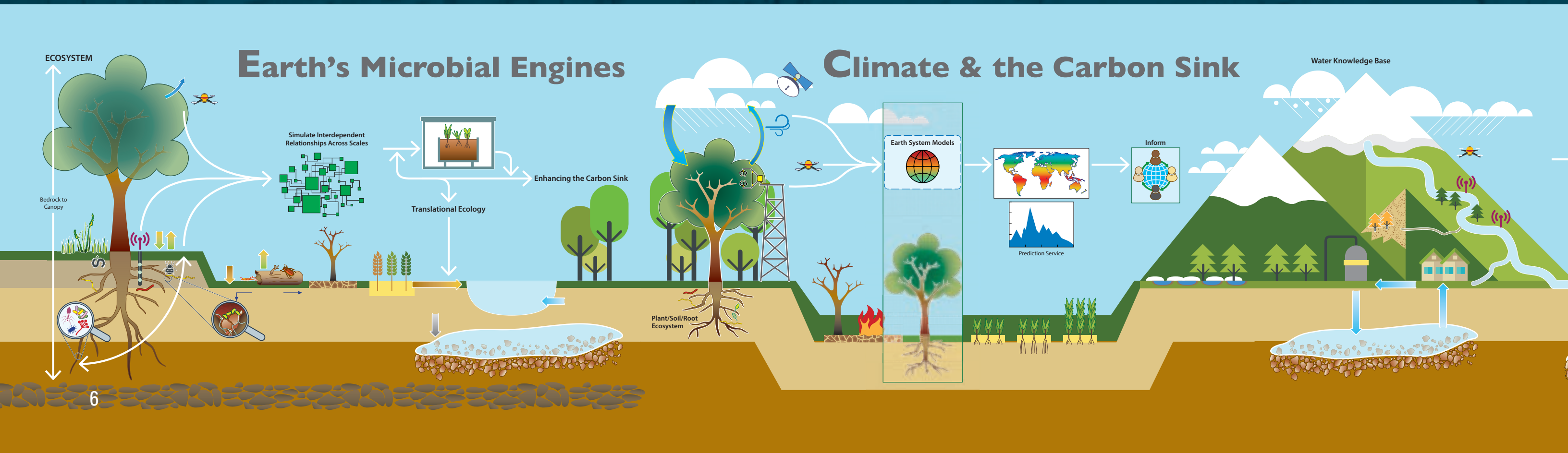
NIMBLE & NETWORKED SENSING SYSTEMS



SCALE-ADAPTIVE DATA & SIMULATIONS TOOLS

These research goals will advance our predictive understanding of interactions and feedbacks across Earth's compartments, from atmosphere to ecosystems to deep subsurface. The breadth of these Grand Challenges explores how small-scale interactions mediate the behavior of entire integrated systems, what in turn influences these small-scale behaviors, and how the combined effect of these interactions on the biogeochemical cycles supports all life on Earth.

EESA's strategic plan will drive the development and integration of new knowledge, tools and capabilities to observe and quantify natural phenomena, to predict future states, and to optimize appropriate solutions and responses. The large-team research efforts required for solving these challenges is a long-term effort. It involves building and strengthening excellent collaborations within and beyond Berkeley Lab, and raising awareness on how science can solve our most pressing national and global issues.



We have an unprecedented opportunity to advance and integrate a suite of tools and expertise required to understand Earth's complexity.

01. EARTH'S MICROBIAL ENGINES

Solving Environmental Challenges with Translational Ecology

GRAND CHALLENGE:
Accurately predict how microbes impact terrestrial ecosystem function, and enable translational ecology approaches that integrate fundamental discovery and multi-scale sensing and simulation capabilities into solutions for enhancing ecosystem function and health

02. CLIMATE AND THE CARBON SINK

Expanding Climate Solutions using Ecosystem Approaches

GRAND CHALLENGE:
Transform our fundamental understanding of the terrestrial carbon sink and ecosystem carbon metabolism, and develop scalable eco-technologies for mitigating climate change and enhancing the resilience of agricultural and other ecosystems

03. FUTURE WATER

Science Solutions for Water Resiliency at Scale

GRAND CHALLENGE:
Transform capabilities to quantify, predict and improve water availability and quality at scale in response to a range of gradual and abrupt perturbations and complex constraints

04. SUSTAINABLE EARTH

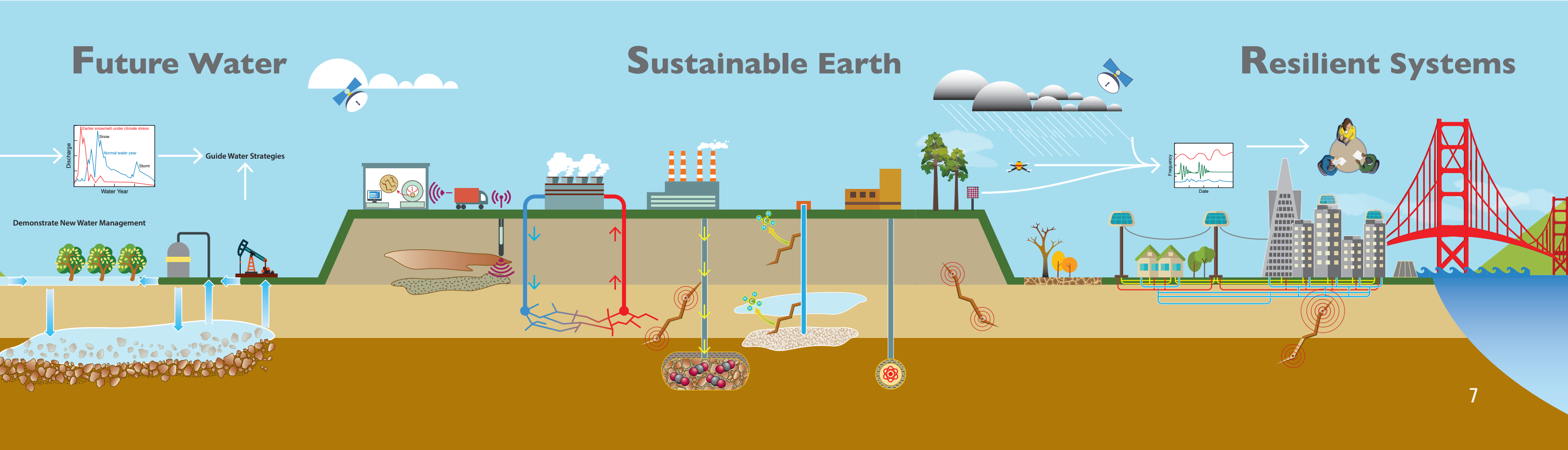
Smarter Use of Subsurface Resources

GRAND CHALLENGE:
Demonstrate 'adaptive control' of subsurface reactions, mechanics, and fluid flow that improve environmental sustainability of energy recovery and storage applications at scale

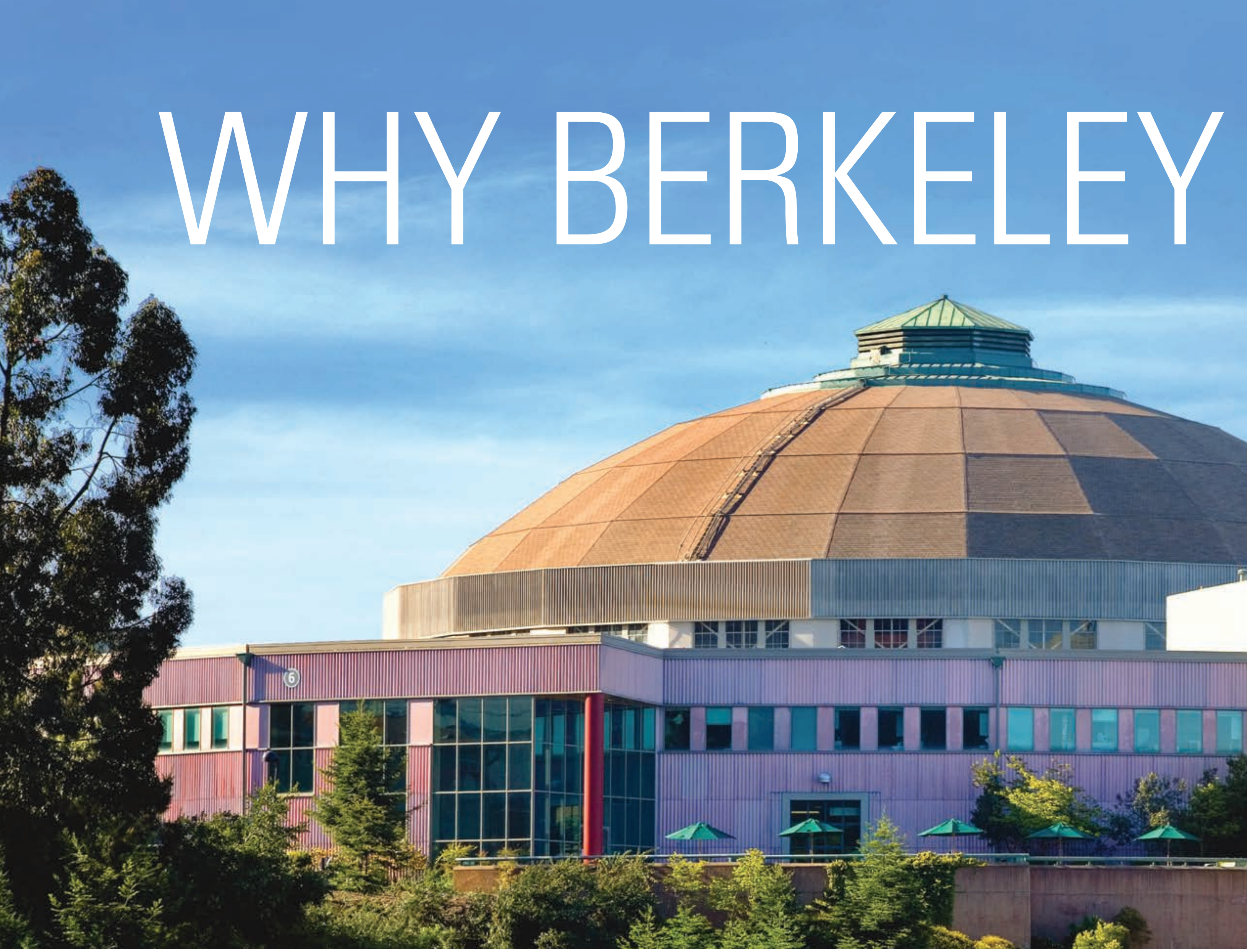
05. RESILIENT SYSTEMS

Strategies for Critical Energy, Water and Built Systems

GRAND CHALLENGE:
Develop and test disruption-ready strategies for resilience of critical energy, water, food and built infrastructure systems using advanced modeling and observational capabilities



WHY BERKELEY

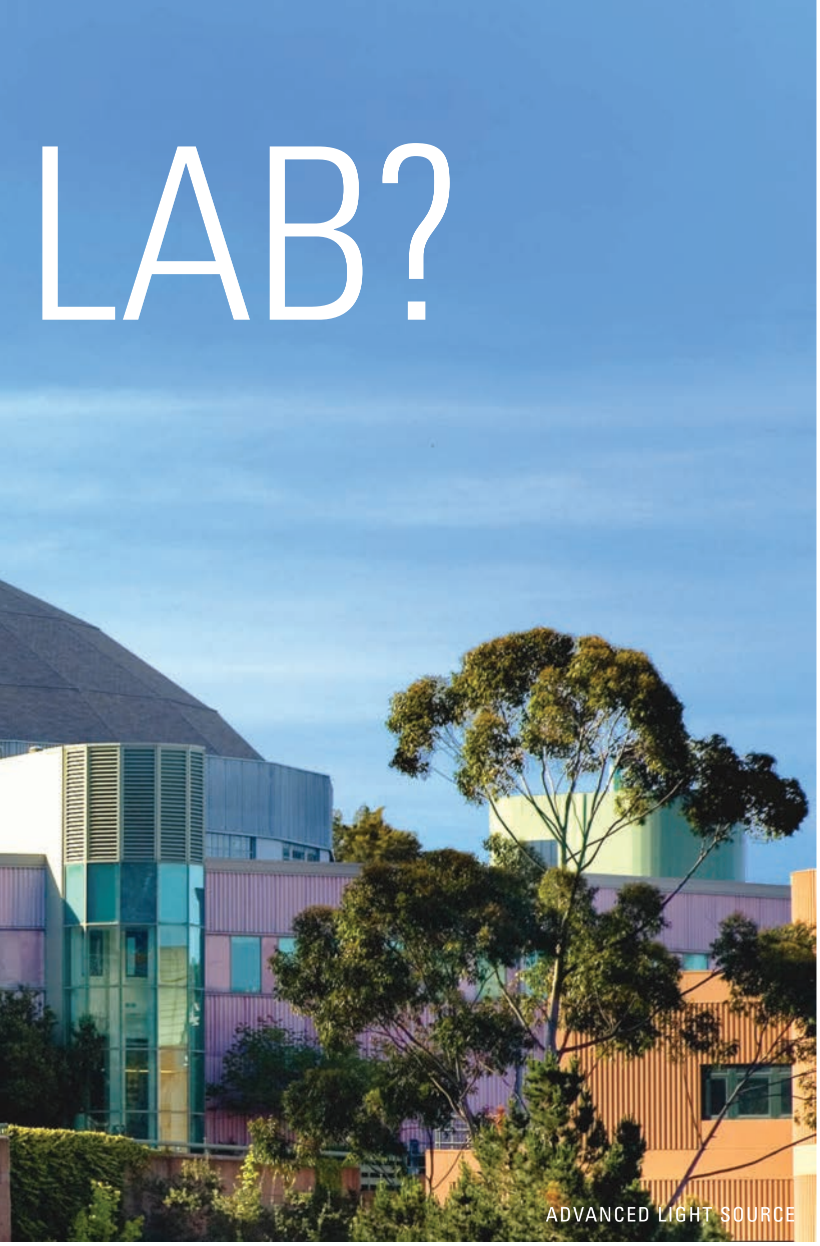


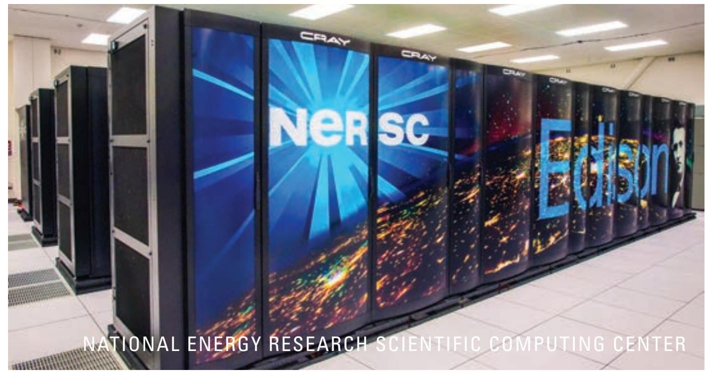
Berkeley Lab's Earth & Environmental Sciences Area (EESA) is a premier research group uniquely suited to take on the identified Grand Challenges. EESA encompasses an extraordinary range of expertise across its two divisions, Climate and Ecosystem Sciences and Energy Geosciences, where interdisciplinary research teams are dedicated to answering the complex energy and environmental questions behind each challenge. Our teams connect several hundred experts, faculty, postdoctoral researchers and students around the major research objectives embodied by each Grand Challenge. By integrating expertise in hydrogeology, ecology, geochemistry, geophysics, and climate sciences to tackle the same large problem, we deliver real benefit to California and the Nation, and provide science solutions to the world.

As a member of the Department of Energy's national laboratory system and with close proximity to the University of California, Berkeley, EESA scientists thrive in our collaborative and resource-rich environment and often take advantage of the extraordinary set of resources, facilities and other assets critical for realizing our scientific mission. Within Berkeley Lab, EESA works closely with partner Areas including Biosciences, Energy Technologies, Energy Sciences, Physical Sciences, and Computing Sciences. The close relationship with the University of California system and the common practice of shared appointments add to the vibrancy of EESA. Our researchers are highly sought after and engage in research with over 50 universities and laboratories in over 30 countries.

The progress we plan to make on the Grand Challenges will be greatly enabled by Department of Energy (DOE) user facilities housed at Berkeley Lab such as the National Energy Research Scientific Computing Center (NERSC), a powerful computing resource we use to predict environmental and earth system trajectories. The Advanced Light Source (ALS) provides bright beams of X-ray light that our scientists use to probe the physical, chemical, hydrological and biological properties of earth materials. The Molecular Foundry provides leading-edge instrumentation to enable the understanding and control of matter at the nanoscale. The DOE Joint Genome Institute (JGI) is dedicated to massive-scale DNA sequencing of microbial

LAB?


ADVANCED LIGHT SOURCE



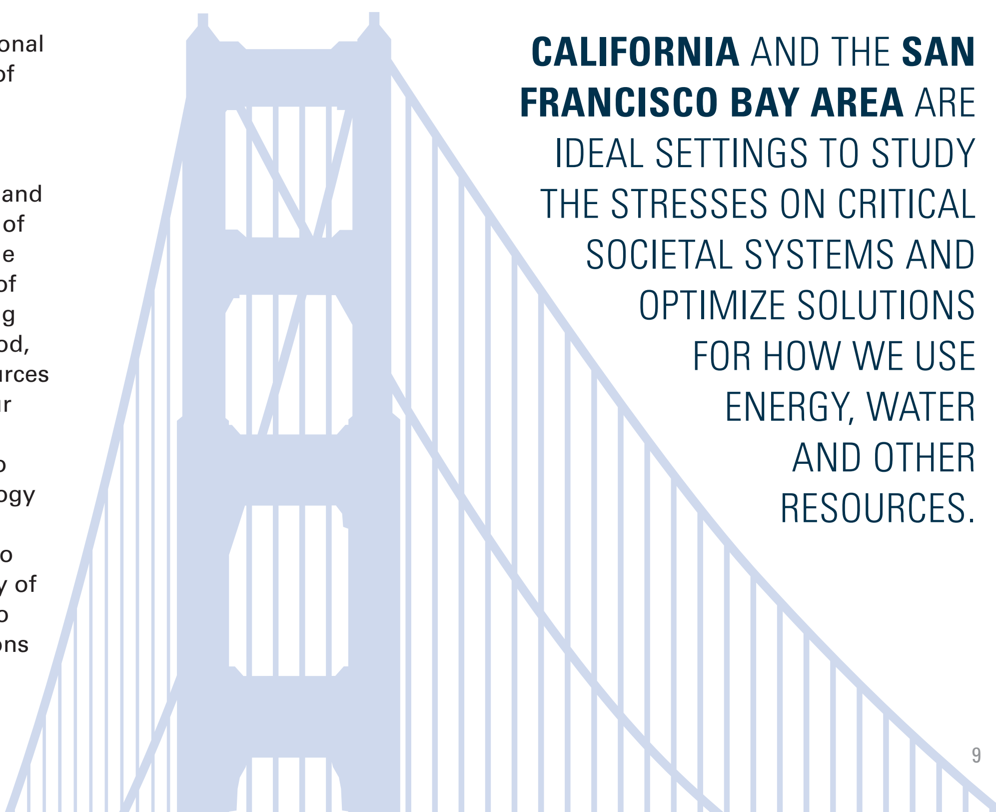
NATIONAL ENERGY RESEARCH SCIENTIFIC COMPUTING CENTER

MOLECULAR FOUNDRY

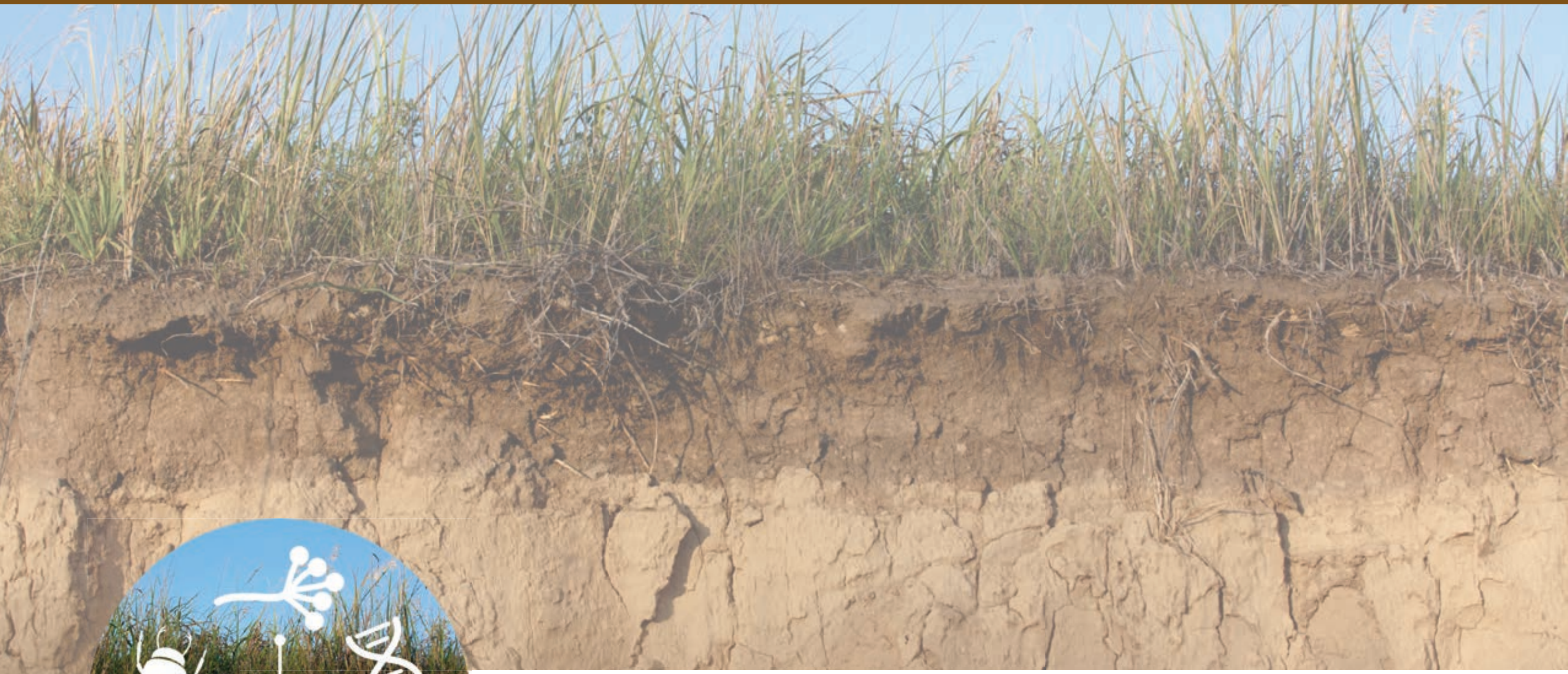

JOINT GENOME INSTITUTE

communities, plants, and fungi—foundational information for improving the prediction of Earth's system behavior.

Located in Berkeley since its founding in 1931, Berkeley Lab's location in California and the San Francisco Bay Area serves as one of the world's best natural laboratories for the chance to observe, up close, the urgency of developing solutions to satisfy the growing and often competing needs for energy, food, ecosystems and water using limited resources and facing an uncertain climate future. Our proximity to Silicon Valley's innovation ecosystem further enables Berkeley Lab to lead the formation of science and technology partnerships that bring together a diverse combination of multidisciplinary science to these Grand Challenges. The Central Valley of California also provides an ideal testbed to explore sustainable and integrated solutions for interdependent energy, water, and agricultural systems.



CALIFORNIA AND THE **SAN FRANCISCO BAY AREA** ARE IDEAL SETTINGS TO STUDY THE STRESSES ON CRITICAL SOCIETAL SYSTEMS AND OPTIMIZE SOLUTIONS FOR HOW WE USE ENERGY, WATER AND OTHER RESOURCES.



01. EARTH'S MICROBIAL ENGINES
SOLVING ENVIRONMENTAL CHALLENGES WITH TRANSLATIONAL ECOLOGY

THE CHALLENGE

We are entering an unprecedented phase in our Earth system. The demand to provide food, energy, and clean water for growing populations is precariously balanced against maintaining and improving the health of our ecosystems. Our biosphere and all living organisms have co-existed and evolved with microorganisms for 3.5 billion years. Microbes possess extraordinary metabolic diversity that enables them to catalyze critical biogeochemical processes that purify our water, build our soils, and regulate the productivity of ecosystems by helping plants acquire nutrients and water, and resist pathogens. This vast metabolic diversity, coupled with the complexity of the physical and chemical environment, makes understanding and predicting the activities of microorganisms a significant challenge.

biogeochemical process

A pathway by which a chemical substance moves through both the biotic (biological) and abiotic (physical rather than biological) components of Earth.

How Earth's microbes will respond to rapid climate change and increasing environmental extremes is uncertain. This imposes large constraints on our ability to predict the metabolic activity of microbes under elevated greenhouse gases, a warmer climate, severe droughts, and other perturbations that influence how ecosystems function. It is critical to be able to quantify, model, and predict microbial-ecosystem feedbacks to better understand the ecology of our planet and to translate this knowledge into environmental strategies. These strategies can lead to environmental solutions that use indigenous microbial functions for maintaining ecosystems that provide healthy soils and plants, clean water, and terrestrial carbon storage.

OUTCOME

Studying the mechanisms by which microbial communities modulate ecosystems, and vice versa, helps us develop a predictive understanding of the potential for naturally occurring microbes to improve the sustainable use of Earth's resources. At the intersection of biology, ecology, biogeochemistry, and the environment, new theories about microbial metabolism and dynamics are leading us to many discoveries about the true impact and potential of microbes—the most diverse and abundant life form on Earth.

For example, microbes are known to play a central role in the biogeochemical cycling of nitrogen and phosphorous in soils. Using microbial-based strategies, we can reduce the need for chemical fertilizers and restore soils damaged through intensive agriculture. Research that connects outcomes from laboratory studies with observations in natural ecological settings will stimulate the development of novel approaches for addressing our most pressing environmental challenges.

This process of 'translational ecology' holds promise for developing solutions that can improve carbon storage in plants and nutrient recycling in soils, mitigation of climate change, remediation of contaminants, extraction of critical minerals, and overall improvements to environmental and human health.

WHY BERKELEY LAB?

Berkeley Lab researchers are at the forefront of fundamental advances to discover, measure, and simulate how microbial communities interact across trophic levels and with the environment. These discoveries reveal how microbes catalyze key biogeochemical processes, and are, in effect, the engines sustaining Earth's biomes. From single microbial genomes to entire ecosystems, we study ecosystem function and resilience using interdisciplinary science that ranges from microbial biology and soil science, to geophysics, remote sensing, and ecosystem ecology.

Berkeley Lab, through our collaborations between the Earth and Environmental Sciences and Biosciences Areas, has a unique capability to study the biology of microbes in the physical and chemical context of a wide range of ecosystems experiencing change. From subsurface bedrock to vegetation canopy, our work covers the tropics and arctic, mountainous watersheds, managed lands, other diverse landscapes, and engineered systems. The breadth and integration of this expertise allows our teams to rapidly mobilize to address emerging research questions, new technologies, and multi-scale ecological understanding for reliably translating fundamental knowledge into environmental solutions.

TRANSLATIONAL ECOLOGY is an integrative trans-disciplinary field of science that promotes actionable research towards the maintenance or enhancement of ecosystem services. Similar to 'translational medicine,' the goal is to use an iterative discovery and modeling approach to rapidly translate new fundamental knowledge of ecosystem function to develop more precise and predictable environmental management strategies.

This process encourages the co-development of knowledge and solutions by stakeholders, including scientists, practitioners, resource managers, and policy makers while always considering the environmental, ethical, and societal implications of new solutions during design.

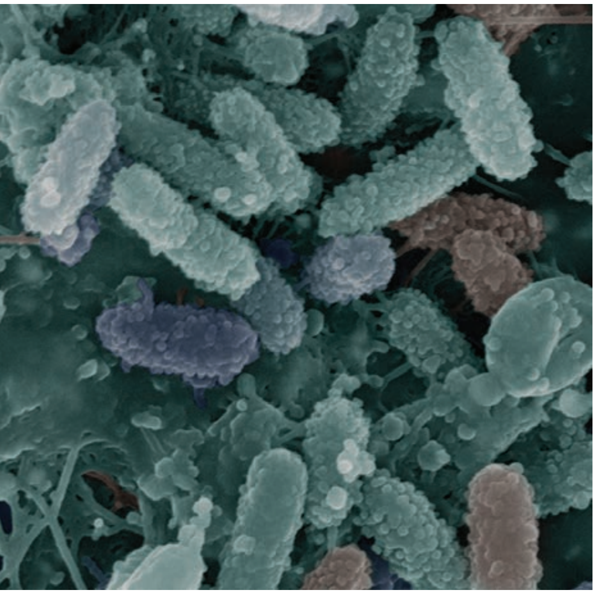
FOUR STRATEGIC RESEARCH OBJECTIVES

THE **GRAND** CHALLENGE

Accurately predict how microbes impact terrestrial ecosystem function, and enable translational ecology approaches that integrate fundamental discovery and multi-scale sensing and simulation capabilities into solutions for enhancing ecosystem function and health

1 Advance the fundamental understanding of microbial metabolic potential and coupled ecological and biogeochemical processes from bedrock to canopy

Microbes, including bacteria, archaea, fungi, and viruses, play a key role in mediating important environmental processes on which terrestrial ecosystem productivity relies. For example, these life forms are central to the flow of carbon and nutrients through complex interdependent networks that include metazoans and plants. By discovering the mechanisms by which microbial communities contribute to processes, such as mineral weathering, aggregate formation, nutrient fixation or mobilization, and organic matter mineralization, we will develop foundational knowledge of soil formation and evolution. This knowledge is key to understanding how carbon and nutrients circulate from the atmosphere and underlying bedrock through the plant canopy *via* the multi-trophic soil foodweb, and how this network of interconnected organisms interacts with soil and subsurface minerals to form stable organic matter and regulate plant productivity.



PRECIPITATION OF TOXIC SELENIUM OUT OF GROUNDWATER BY MICROORGANISMS

Building this knowledge-base through the integration of physical, chemical, and biological sciences will allow us to improve predictions of how global change and land management strategies will impact ecosystem biogeochemical networks and ecosystem function. Critical interfaces such as the rhizosphere, the detritusphere, the capillary fringe, and the hyporheic zone provide natural gradients to study the relationship between microbial metabolism and the chemical environment. The development of highly controlled synthetic soil ecosystems will be key to test hypotheses and deduce causal mechanisms. Our partnership with scientists in the Biosciences Area is an important asset in achieving these goals.

5-YEAR GOALS

- Uncover mechanisms of microbial assimilation, mobilization, and transformation of carbon, phosphorus, nitrogen, and metals in plant material, soil, or subsurface minerals
- Identify microbial mechanisms impacting soil aggregate formation and stability
- Develop new approaches to derive quantitative trait information from ‘omic analyses, and non-destructive imaging of complex microbial communities
- Demonstrate the importance of metazoans and their microbiomes to biogeochemical transformations by defining the direction and strength of trophic interactions within the soil foodweb using molecular and isotopic approaches

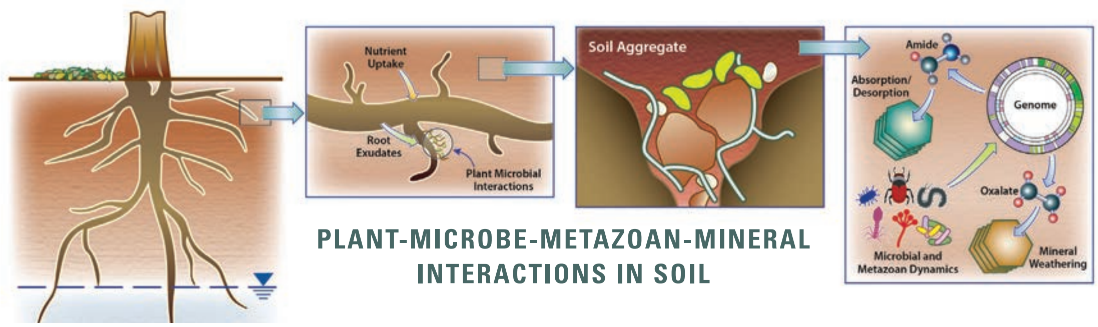
10-YEAR GOALS

- Build a mechanistic representation of the microbial, metazoan, and plant roles in soil formation and evolution using the newly discovered microbial metabolic processes
- Develop a process understanding of coupled hydrological and biogeochemical feedbacks that regulate nutrient recycling, water retention, contaminant biotransformation, and ecosystem productivity in terrestrial systems

2 Develop multi-scale capabilities to accurately sense and simulate biological-environmental feedbacks

The emergence of environmental 'big data', available through multi-scale environmental sensing and genome sequencing technologies, can be combined with powerful computational capabilities. This combination allows the development of mechanistic models of how microbes interact within complex ecosystem networks and how these networks respond to environmental stresses to influence ecosystem functioning and productivity.

With the discovery of new processes, Berkeley Lab researchers curate and extract information from diverse biological-environmental datasets, taking advantage of multi-scale ecosystem sensor data and multi-omics approaches. This knowledge is used to develop the next generation of models, which can answer questions about the relationships between microbial metabolic diversity and ecosystem function. For example, our scientists explore the key ecological constraints that select for the assembly, structure, and function of microbial groups in a particular environment. In diverse settings, ranging from the root zone to permafrost to tropical forests and watersheds, we develop and use these next-generation microbe-ecosystem models to uncover how ecology, evolution, and environmental variation interact to direct the flow of energy, nutrients, and water through terrestrial ecosystems.



PLANT-MICROBE-METAZOAN-MINERAL INTERACTIONS IN SOIL

Multi-scale interactions involving plants, microbes, metazoans, and their metabolic products with minerals alter soil chemical and physical properties and govern carbon, nutrient, and elemental cycling

5-YEAR GOALS

- Develop metabolic and biogeochemical models of key microbial interactions in soil formation and evolution, and use them to understand nutrient exchange between plants and microbes, and their responses to perturbation, including drought and elevated atmospheric CO_2
- Develop equilibrium transport models for how plants, microbes, and soil minerals compete for nutrients, and how this impacts plant productivity and soil nutrient retention
- Develop new sensing approaches to monitor biological-environmental feedbacks *in situ*, including methods for using surface features such as vegetation chemistry to predict subsurface biogeochemistry and hydrology

10-YEAR GOALS

- Develop new ecosystem models built on a novel theoretical framework, which can predict the properties of surface and subsurface ecological networks, including plants, microbes, and metazoans, and are designed to represent the process-level interactions among carbon storage, nutrient recycling, water retention, and contaminant biotransformation

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HOW WILL MICROBES IN THE FOODWEB RESPOND TO ELEVATED ATMOSPHERIC CO_2 OR TO NEW TEMPERATURE AND HYDROLOGICAL PATTERNS THAT MELT PERMAFROST OR PROLONG DROUGHTS?

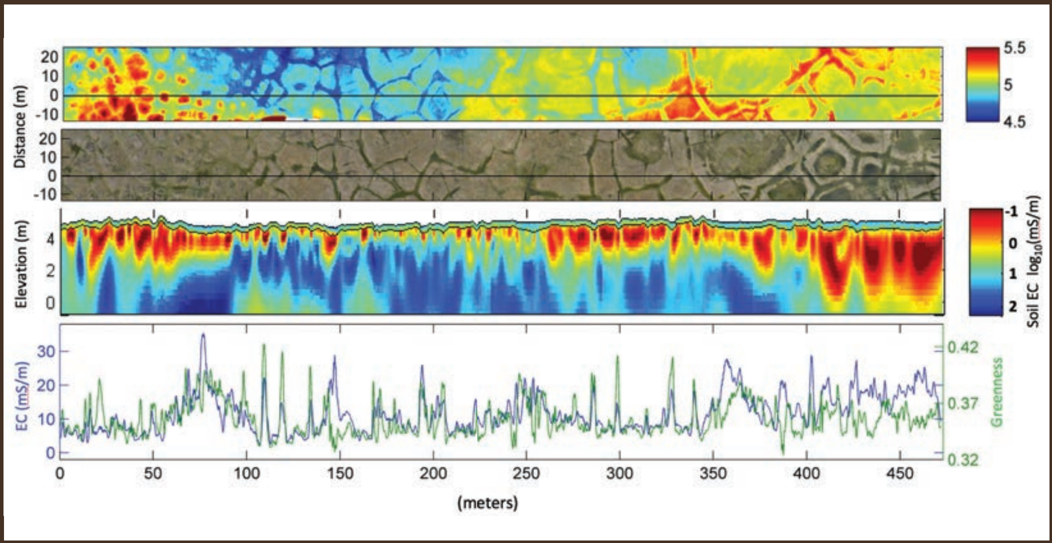
Nimble and networked ecosystem sensors and new scale-adaptive simulation capabilities can help predict how key plant-soil-microbe interactions change in response to environmental stresses such as extreme temperatures and drought

3 Document the impact of global change and other perturbations on microbial processes in soil and subsurface systems and the resulting impacts on ecosystem function

We do not yet know the impacts of rising global temperatures and other environmental stressors on microbial function and the potential this has to cause unexpected disruptions in the ecosystem services on which we rely. For example, how will microbes in the subsurface foodweb respond to elevated atmospheric CO_2, or to new thermal and hydrological patterns that melt permafrost or induce prolonged droughts? It is possible that plant productivity in natural and managed systems will be affected if these microbial responses impact the mobilization of carbon and key plant nutrients, such as nitrogen and phosphorus, across terrestrial-aquatic interfaces and other ecotones.

The convergence of climate with changing patterns of land use can also lead to contaminant transformation and mobilization that releases metals or organic pollutants into the subsurface foodweb. These releases can, in turn, disturb the biogeochemical and trophic networks in ecosystems that maintain our healthy soils and clean water. By combining Berkeley Lab's predictive capabilities in climate modeling and new approaches to sense and simulate biological-environmental feedbacks in ecosystems from microbial to ecosystem scale, we can translate fundamental knowledge into new science-based solutions.

COUPLING SURFACE AND SUBSURFACE PROCESSES



Sensing technologies reveal interactions occurring across different terrestrial system compartments, from subsurface bedrock to vegetation canopy. These approaches are being used for sensing surface-subsurface property dynamics over time to reveal information about interactions occurring from local to regional scales as a result of climate change.

Unmanned Aerial Systems (UAS) autonomously imaging surface microtopography and vegetation properties such as 'greenness' in the Arctic tundra. Greenness (green line) is strongly correlated with electrical conductivity (EC) of the top 20 cm of soil, which is a proxy for soil water content.

5-YEAR GOALS

- Quantify the impact of precipitation and temperature extremes on the soil biome, and derive generalizable metabolic principles that predict impacts on soil structure, nutrient retention, and carbon turnover
- Quantify and predict how plants and microorganisms help retain nutrients in ecosystems, and the impact of thermal and hydrologic perturbations on nutrient loss
- Observe and simulate how elevated CO_2 alters carbon and nutrient allocation within plants and to microbial partners, and whether this alters ecosystem nutrient availability

10-YEAR GOALS

- Develop a bedrock-to-canopy package of nimble-and-networked sensors that can be rapidly deployed to quantify ecosystem responses to natural and anthropogenic disturbances
- Build a network of virtually connected ecosystem observatories representing climate-vulnerable landscapes, which uses integrated multi-scale sensing and simulation to provide real-time information about biogeochemical responses to perturbations

BioEPIC The Biological & Environmental Program Integration Center (BioEPIC) is a collaboration that will align strategic goals and leverage Berkeley Lab's expertise in Earth and Environmental Sciences and Biosciences to build a unique laboratory facility dedicated to the study of how microbial communities respond to and shape environmental systems. BioEPIC consists of four science and technology 'cores' that span a microbe-to-biome scale understanding of soil-microbe-plant systems by building a powerful capability to virtually link controlled laboratory experiments with environmental observatories allowing rapid translation of new understandings to real-world challenges.

EcoSENSE - nimble and networked sensing suites for quantifying biological-environmental feedbacks

EcoTECH - technology suites that quantify fine-scale physical, chemical, and biological mechanisms

EcoFAB - highly controlled laboratory-based biomes across scales

EcoSIM - multi-scale computational models for simulating complex microbe-environmental feedbacks

4 Translate ecological understanding into predictable solutions for environmental challenges

An improved understanding of the complex and integral role that microbes play in our ecosystems will guide the development of new strategies to reduce environmental damage and optimize our responsible access to the energy, food and water resources we need. Knowledge of microbial traits from controlled experiments can be translated and scaled up to develop approaches for restoration ecology, which have potential to improve responses to a wide range of environmental challenges. For example, precision control of microbial physiology and metabolism in characterized environments can promote the formation of soil organic matter, and can bring co-benefits, such as improvements to plant nutrition in marginal lands, and stress resistance to drought, salinity, and pathogens. Ongoing collaborations with the Biosciences Area are key to developing technologies for precision control of microbes and plants to uncover molecular mechanisms. Other enhancements can prevent nutrient runoff and algal blooms, treat contaminated water to recover critical materials, and remediate metal, radionuclide or hydrocarbon contamination.

Diagnosing soil 'health' and restoring ecosystems by promoting resilient multi-trophic networks can help mitigate severe climate-accelerated impacts. Translational ecology approaches build on our fundamental understanding of ecosystem components, and provide the ability to predict the effect of customized management strategies designed for beneficial environmental outcomes.

5-YEAR GOALS

- Demonstrate that knowledge of microbial traits from reconstructed genomes can be used together with data on environmental gradients to select and cultivate important microorganisms, and to identify novel metabolic pathways
- Test the reproducibility of using select microbial traits for improving plant nutrition under limiting conditions
- Show proof-of-principle that soil structure and organic carbon inputs can be enhanced by manipulating microbial physiology and biochemistry

10-YEAR GOALS

- Translate our understanding of newly discovered microbial enzymes to enhance/diversify the synthesis of microbial bioproducts
- Use systems ecology understanding to develop new microbial interventions that improve the treatment of contaminants in groundwater and municipal and industrial wastewater
- Design land management strategies that effectively regulate the nitrogen cycle to reduce, and, ultimately, eliminate the negative impacts of excess nitrogen on soil health, waterways, and climate

SELECT PROJECTS, FOUNDATIONAL SPONSORS & PARTNERS

PROJECTS

Berkeley Synchrotron Infrared Structural Biology (BSISB) Program

Bioenergy Biology Projects (JBEI, LLNL Biofuels SFA, EBI)

Biological Feedbacks Scientific Focus Area

Belowground Carbon Cycling Scientific Focus Area

Ecosystems and Networks Integrated with Genes and Molecular Assemblies (ENIGMA)

Interoperable Design of Extreme-scale Application Software (IDEAS)

Marin Carbon Project

Microbes-to-Biomes (M2B) LDRD

Next Generation Ecosystem Experiments NGEE-Tropics & NGEE-Arctic

Research for Sustainable Bioenergy

Systems Biology of Carbon Cycling

Tomographic Electrical Rhizosphere Imaging (TERI)

UC Consortium for Drought and Carbon Management (UC DroCaM)

Watershed Function Scientific Focus Area

SPONSORS

Advanced Research Projects Agency-Energy (ARPA-E)

DOE Office of Science, Biological and Environmental Research (BER)

Energy Biosciences Institute (EBI)

National Institute of Health (NIH)

National Science Foundation (NSF)

PARTNERS

Advanced Light Source

Berkeley Lab Biosciences Area

Berkeley Lab Computing Sciences Area

California Department of Food and Agriculture (CDFA)

DOE Systems Biology Knowledgebase (DOE-KBase)

Joint BioEnergy Institute

Joint Genome Institute

Molecular Foundry

National Energy Research Scientific Computing Center (NERSC)

Noble Foundation

Environmental Molecular Sciences Laboratory at PNNL

Lawrence Livermore National Laboratory

UC Berkeley

UC Davis

UC Division of Agriculture and Natural Resources

U.S. Department of Agriculture (USDA)

U.S. Forest Service

02. CLIMATE AND THE CARBON SINK

EXPANDING CLIMATE SOLUTIONS USING **ECOSYSTEM APPROACHES**

THE CHALLENGE

Earth's land ecosystems provide us with food, fuel, and essential climate-regulating services, such as the carbon sink. Each year, terrestrial ecosystems, such as prairies and forests, take up about one-third of all anthropogenic CO_2 emissions. Currently, these ecosystems fix more CO_2 by photosynthesis than they release in respiration, and store this carbon as plant biomass and organic material in soils. This imbalance acts as a 'sink' for carbon by reducing CO_2 concentrations in the atmosphere and diminishing the impact that anthropogenic CO_2 emissions would have on the climate.

Remarkably, this carbon sink has been increasing in recent decades, keeping pace with our rising emissions and absorbing even greater amounts of CO_2. The relevant mechanisms are uncertain. If the sink slows down or is reversed by the impacts of human disturbance and the stresses of climate change, it would lead to more rapid build up of atmospheric CO_2 and an increase in global warming. A mechanistic understanding of how the carbon sink functions could improve predictability and the ability to develop scalable strategies for protecting and enhancing it.

OUTCOME

Improving scientific knowledge of terrestrial ecosystem function will allow us to develop transformational strategies to protect and enhance the ability of these Earth systems to sequester carbon. In a future where decarbonized energy dramatically lowers greenhouse gas emissions, the land carbon sink has the potential to absorb additional CO_2 to help meet ambitious climate-change mitigation goals. Targeting specific enhancements to the land carbon sink will also provide co-benefits, such as healthier soils, more productive ecosystems and carbon-neutral bioenergy. By advancing the science of the carbon sink, we will broaden climate protection strategies to guide society on the path to a stable climate and sustainable future.

Eco-technologies are ecological solutions that require an advanced understanding of the structure and function of Earth's ecosystems to harness natural processes and leverage their beneficial effects for society while minimizing ecological disruption.

WHY BERKELEY LAB?

Berkeley Lab researchers are transforming our understanding of how carbon cycles between atmosphere, plants, and soils. The process insights and mechanistic models we are developing provide a foundation for new strategies to protect and enhance the terrestrial carbon sink. Across the diverse ecosystems of the world, from deserts to tropical rain forests, we study how climate shapes these systems and, in turn, how changing landscapes influence climate.

Using some of the most advanced scientific tools available, we probe the dynamics of the biosphere, scaling from a microbial colony that stabilizes carbon in a soil particle to the regional interplay between forests and clouds that give rise to heavy rain storms or drought. Our scientists develop Earth System Models to accurately represent these interactions by combining theories about physical and biological processes together with massive data sets from observed environmental conditions. Earth System Models harness the Lab's high-powered computational capabilities to produce reliable, quantitative predictions of how human activities and climate change may alter the trajectory of the carbon sink, and what society can do about it.

?

WILL TROPICAL, ARCTIC AND OTHER ECOSYSTEMS CONTINUE TO ACT AS LARGE SINKS OF CARBON IN THE 21ST CENTURY?

WHERE IS THE SINK MOST VULNERABLE?

CAN WE USE ECO-TECHNOLOGIES TO PROTECT AND ENHANCE THE CARBON SINK IN A CHANGING CLIMATE?

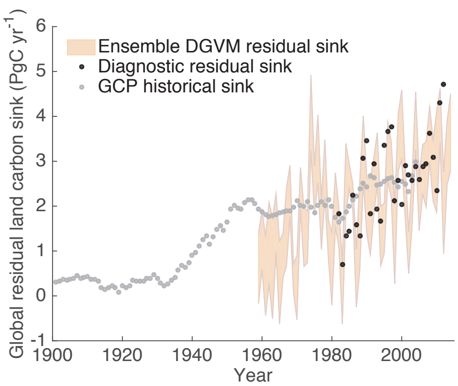
FOUR STRATEGIC RESEARCH OBJECTIVES

THE **GRAND** CHALLENGE

Transform our fundamental understanding of the terrestrial carbon sink and ecosystem carbon metabolism, and develop scalable eco-technologies for mitigating climate change and enhancing the resilience of agricultural and other ecosystems

1 Develop a fundamental understanding of the terrestrial carbon cycle and predict the trajectory of the carbon sink

Experiments, observations and simulations indicate that changes in the terrestrial carbon cycle depend on a complex network of interactions among microbes, plants, and abiotic processes, covering a spectrum of spatial and temporal scales. Berkeley Lab researchers focus on using experimental observations and measurements to improve land and Earth System Models that can predict function of land ecosystems at various scales, from a specific site to continental and global scale. This work also includes the study of major perturbations to atmospheric and oceanic circulation from El Niño/La Niña phenomena.



LONG-TERM CHANGES IN THE LAND CARBON SINK ESTIMATED VIA MULTIPLE METHODS: AN ENSEMBLE OF DYNAMIC GLOBAL VEGETATION MODELS (DGVMS), THE GLOBAL CARBON PROJECT (GCP) RESIDUAL SINK APPROACH, AND A SATELLITE-DRIVEN DIAGNOSTIC MODEL.

Our ongoing work focuses on studying soil and plant nutrient biogeochemistry and vegetation dynamics in diverse landscapes, ranging from the Tropics to the Arctic, which brings together a critical mass of observational, experimental and modeling scientists, and their advanced methods.

5-YEAR GOALS

- Develop scale-adaptive simulation capabilities that incorporate high-resolution ecosystem changes into global models and focus on linking numerical representations of land use and vegetation change across spatial scales.
- Improve process understanding of nutrient and water coupling in the soil and plant system, plant and microbial allocation and acclimation, coupled biological-physical soil organic matter protection mechanisms, and the effects of climate extremes.

10-YEAR GOAL

- Develop process-specific predictive understanding of changes in managed lands and natural ecosystems
- Apply the resulting models to characterize the uncertainty of terrestrial carbon stock trajectories under changing climate (including CO_2, deposition, land use and land cover change), and potential leverage points for introducing new carbon management tools and technologies to enhance the carbon sink

HIGH-RESOLUTION FOREST CANOPY NORTH OF MANAUS, BRAZIL. IMAGED USING AN UNMANNED AERIAL SYSTEM (UAS) FOR FORESTS.

2 Advance the predictive understanding of the changing climate and its interaction with ecosystems

The land and atmosphere are highly-coupled systems where changes in one directly influence the other with the possibility of positive feedback loops that will further alter climate and the carbon cycle. Understanding the role of land surface processes on the long-term evolution of climate and extreme events will improve our ability to predict extreme climate events.

Atmospheric convection, the dynamics of cloud formation, and precipitation all depend strongly on land surface processes such as evaporation and plant transpiration. These represent areas where we need significantly improved predictive models. Berkeley Lab's expertise in atmospheric physics and land-atmosphere interactions coupled with high performance computing capabilities is pushing the boundaries of high-resolution climate modeling needed for region-specific impact studies to guide mitigation strategies.

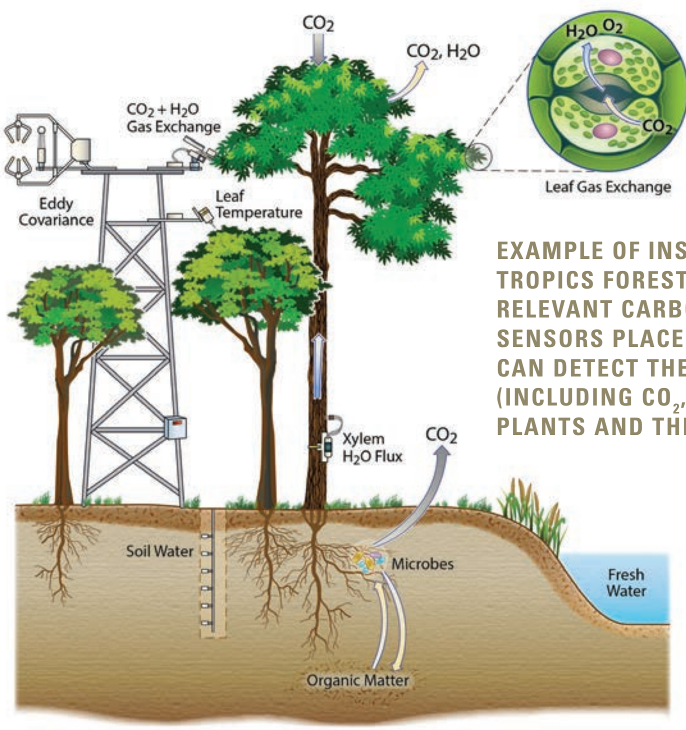
By using an understanding of atmospheric physics to distinguish long-term climate changes from variability, we are developing an understanding of future climate changes and the long-term evolution of the Earth system and the terrestrial ecosystems on which it depends.

5-YEAR GOALS

- Advance the understanding of convection and other important atmospheric dynamics processes by improving our ability to both model the role of vegetation dynamics in land-atmosphere interactions, and predict the impacts of land use on climate

10-YEAR GOALS

- Develop significantly higher spatial and temporal resolution simulation capabilities that improve prediction of the frequency of co-occurrence of damaging climate events, such as flash flooding, high winds, droughts, and heat waves



EXAMPLE OF INSTRUMENTING NGEE-TROPICS FORESTS SITES TO MEASURE RELEVANT CARBON AND WATER FLUXES. SENSORS PLACED IN THE TREE CANOPY CAN DETECT THE EXCHANGE OF GASES (INCLUDING CO_2, H_2O AND O_2) BETWEEN PLANTS AND THE ATMOSPHERE.

PLANT PROCESSES AND GLOBAL CHANGE

Berkeley Lab is advancing understanding of how fundamental processes, such as plant biochemistry and physiology, control ecosystem-scale functions that are critical to the earth system.

One such process, photosynthesis, is fairly well understood at the molecular level, but new approaches are needed to scale from cells to ecosystems and the globe. Other processes, such as plant respiration, are poorly understood and therefore poorly represented in the Earth System Models used to simulate ecosystem interactions with climate. These knowledge gaps are critical because together these processes are responsible for ecosystem functions such as converting photosynthetic carbon gain into new biomass, maintaining vigor under extreme climate conditions, and obtaining nutrients from soils.

Deeper insight into biological processes will significantly improve modeling of ecosystem feedbacks in the climate system and plant response to elevated atmospheric CO_2, resulting in more accurate projections of the carbon sink and future climate.

3 Identify the geographic-specific vulnerability and potential of the carbon sink

The climate system and the carbon cycle are strongly coupled at a global scale, requiring Earth System Models to reflect key features of land ecosystems as well as atmospheric variability and change. From arctic ecosystems rich in permafrost-protected carbon to tropical forest carbon sinks, the fundamental need to accurately quantify vulnerabilities and feedbacks over decade-to-century scales varies greatly across ecosystems.

Berkeley Lab's deep expertise in land and atmospheric observations is tightly coupled to the development of advanced Adaptive-Mesh Refinement and Exascale computing to quantify climate-ecosystem feedbacks. Developing these regionally and globally robust Models of land ecosystems will enable us to quantify and predict the untapped opportunities and vulnerabilities for land carbon storage and how it will be impacted in response to climate and ecosystem changes. Berkeley Lab has extensive, ongoing research focused on developing advanced land and Earth System Models. We are challenging these models with diverse and distributed data sets on atmospheric states and terrestrial ecosystems including Arctic tundra and tropical forests. Many unique observations are used to evaluate key features of the system, such as cloud-formation observations to inform prediction of atmospheric-model radiative processes.

HIGH-RESOLUTION SIMULATION OF HURRICANE KATRINA USING THE COMMUNITY EARTH SYSTEM MODEL.

5-YEAR GOALS

- Develop process-rich models at regional-kilometer and local-meter grid scales and challenge models with observations to improve prediction of feedbacks and impacts of global change
- Develop above- and below-ground networked observations coupled with new modes of handling diverse terrestrial system datasets

10-YEAR GOALS

- Develop improvements to Earth System Model fidelity across land and atmospheric components
- Expand the use of data-informed modeling approaches for evaluating the ability of Earth System Models to predict long-term and large-scale vegetation change.

ADAPTIVE-MESH REFINEMENT AND EXASCALE COMPUTING

Berkeley Lab environmental and computational scientists are developing **Adaptive-Mesh Refinement** (AMR) models that simulate key atmospheric **processes** using very high spatial resolution atmospheric representations.

AMR models are able to better resolve tropical cyclones, and the effect of mountains on precipitation and convective cloud systems. The same modeling capabilities can be applied to ecosystem-climate interactions. AMR requires the computational power offered by Exascale computing systems, which are capable of more than one exaFLOPS, or a billion billion calculations per second.

4 Develop and test scalable eco-technology strategies for natural and managed systems

New eco-technologies geared toward enhancing the carbon sink have the potential to also offer co-benefits, such as improved forest resilience to drought or boosting crop yields. Our ongoing work on the core mechanisms of the plant-soil system will enable the development of scalable strategies to steward ecosystem services, maintain healthy soils, and reduce the impact of anthropogenic activities on climate and the world's ecosystems.

> **EESA research will expand the option space for decision makers by developing approaches to protect and enhance the carbon sink that are not only environmentally safe and sustainable, but also have significant co-benefits and can scale to meet the climate challenge.**

Scalable eco-technologies can include novel strategies for drought resilience, manipulating soil microbial metabolism to restore degraded lands, and increasing plant productivity for bioenergy. New decision-support tools will provide policy-actionable projections of the terrestrial carbon sink and other ecosystem services, as well as evaluate climate consequences of land use and identify ecosystem carbon stores in need of protection.

MANAGING CARBON WITH ECO-TECHNOLOGIES

Agricultural systems have the potential to simultaneously sequester carbon in soil while meeting goals for food and bio-energy production. Additional research is needed for developing viable eco-technologies and documenting successful approaches.

SOIL CARBON PROCESSES

Enhancing soil carbon stocks can have many environmental co-benefits, including increasing ecosystem fertility and resilience to drought. Sustainable and scalable management strategies require tailoring solutions to local contexts and developing deep process knowledge.

5-YEAR GOALS

- Develop a research roadmap for translating fundamental science results into ecological approaches to protect and enhance the carbon sink
- Beta-test a computational architecture for data-constrained models and geographic-specific carbon sink function

10-YEAR GOALS

- Evaluate eco-technologies for potential impact in rebuilding soils degraded by intensive agriculture
- Design a forecasting service that predicts carbon sink function with regional-level precision and identifies eco-technologies that provide resilient mitigation options

SELECT PROJECTS, FOUNDATIONAL SPONSORS & PARTNERS

PROJECTS

Accelerated Climate Modeling for Energy (ACME)

AmeriFlux Management Project

ARM Southern Great Plains and Carbon Project

Atmospheric System Research (ASR)

Belowground Carbon Cycling Scientific Focus Area

Biological and Environmental Program Integration Center (BioEPIC)

Biogeochemical Cycle Feedbacks

Biogeochemistry-Climate and Soil Warming (BGC) Scientific Focus Area

Calibrated and Systematic Characterization, Attribution, & Detection of Extremes (CASCADE)

California Soil Carbon and Response to Drought Catalyst Award

Hyperion Climate Decision Science

International Land Model Benchmarking (ILAMB)

Lighthouse

Microbes-to-Biomes (M2B) LDRD

MULTISCALE

Next Generation Ecosystem Experiments NGEE-Tropics & NGEE-Arctic

Soil Carbon Management

SPRUCE (Spruce and Peatland Response Under Climatic and Environmental Change)

Watershed Function Scientific Focus Area

SPONSORS

DOE Office of Science, Biological and Environmental Research

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DOE Office of Energy Efficiency and Renewable Energy, Bioenergy Technologies Office

DOE Advanced Research Projects Agency-Energy (ARPA-E)

California EPA Air Resources Board

National Aeronautics and Space Administration

National Oceanic and Atmospheric Administration

National Science Foundation

San Francisco Public Utilities Commission

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DOE National Laboratories

Environmental Molecular Sciences Laboratory

Joint Genome Institute

National Center for Atmospheric Research

National Energy Research Scientific Computing Center

National Institute of Amazonian Research (INPA)

Smithsonian Tropical Research Institute

University of California and other universities

03. FUTURE WATER

SCIENCE SOLUTIONS FOR **WATER RESILIENCY** AT SCALE

THE CHALLENGE

Water is central to the well-being of thriving societies and a healthy planet, yet its future is unclear. Changing rain and temperature patterns and more frequent extreme weather events are significantly reshaping the water cycle and have serious implications for future management of our water systems. California and other regions are facing reduced snowpacks, prolonged droughts, and severely depleted groundwater resources. Water quality and quantity is tightly linked to our energy and agricultural systems, and vulnerabilities in one increase risk to the others.

> THE MAJOR CHALLENGE IS TO ADAPT HOW WE USE WATER RESOURCES FOR ENERGY PRODUCTION, IRRIGATION AND OTHER KEY SOCIETAL NEEDS IN AN ENERGY-CONSTRAINED AND UNCERTAIN CLIMATE FUTURE

Effective future water management solutions, which incorporate scientific knowledge about changing water cycles and complex system interdependencies, are needed to make decisions about water delivery that meet the rising demand and increasing uncertainty. New water management strategies require coordinated scientific and technological advances to significantly increase our understanding of water availability and quality, and to develop optimized and energy-efficient options for water treatment, reuse and storage.

> THE RESULTS OF BERKELEY LAB RESEARCH WILL OFFER A RANGE OF TECHNOLOGY OPTIONS AND STRATEGIES TO OPTIMIZE WATER RESOURCE PLANNING UNDER CHANGING SCENARIOS

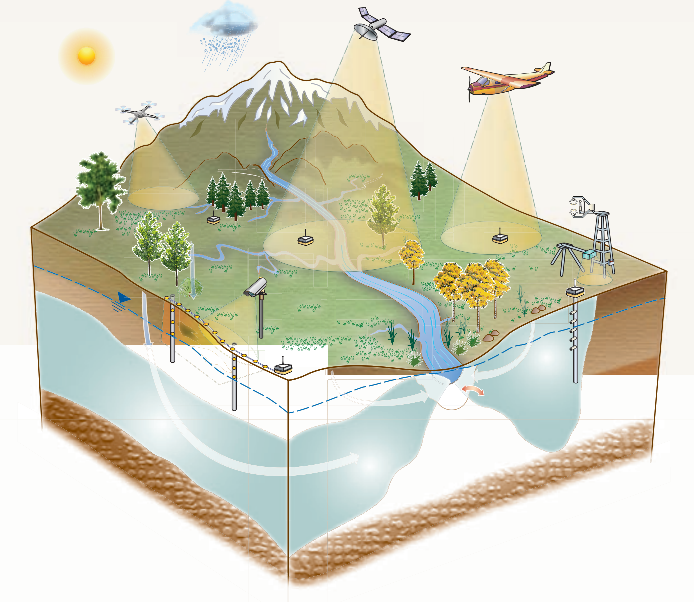
OUTCOME

A water-resilient future will require new strategies to manage water as a sustainable resource, ensuring healthy natural ecosystems, energy efficiency, agricultural productivity, and overall economic prosperity. Resilient strategies will require consideration of a range of geographically-variable stresses and states, ranging from water shortages caused by changes in timing or magnitude of snowmelt in pristine mountainous systems, to reuse of produced waters in regions heavily impacted by subsurface energy production. Berkeley Lab research will provide insights and technologies that will allow water managers to make scientifically-informed decisions and to deploy strategies that are optimized for future conditions.

WHY BERKELEY LAB?

Berkeley Lab is building a scientific foundation to guide resilient water management strategies for an energy-constrained and uncertain climate future. Through our foundational projects, we are developing scalable approaches to simulate hydroclimate perturbations and their influences on watershed dynamics, which will give us greater confidence in ‘when’ and ‘where’ future water will be available. We are exploring how increasingly frequent threats to watersheds, such as floods, droughts and early snowmelt, influence water quality and quantity.

To enhance water resiliency, we pair new understanding of water distribution and quality with the development of novel techniques for storing water ‘at scale’ in the subsurface, optimized for future climate conditions and tested in dedicated field observatories. To alleviate pressure on our over-allocated water resources, we are developing new approaches for the treatment of unconventional water sources for purposed reuse. Our water science is underpinned by Berkeley Lab’s proven capabilities in collecting environmental ‘big data’ and developing analytical tools to extract knowledge from diverse environmental datasets, which can be used by decision-makers dealing with difficult water challenges in their regions.



OBSERVING WATERSHED FUNCTION

Berkeley Lab is establishing a well-instrumented community field observatory within a mountainous headwaters catchment, and using the site to develop and test how hydrological perturbations (such as floods and droughts) contribute to aggregated downgradient discharge of water and exports of nutrients, carbon and contaminants.

To improve prediction of future watershed function, scale-adaptive modeling approaches are being developed to simulate coupled climate, hydrological and biogeochemical dynamics. This first-of-a-kind watershed model will be useful for understanding how watersheds will respond to increasingly frequent extreme events and for exploring the interplay between climate, water supplies, and energy resources.

FOUR STRATEGIC RESEARCH OBJECTIVES

THE **GRAND** CHALLENGE

Transform capabilities to quantify, predict and improve water availability and quality in response to a range of gradual and abrupt perturbations and complex constraints

1 Predict how future hydroclimate forcings and complex environmental interactions within watersheds contribute to cumulative down-gradient discharges of water, nutrients and contaminants

Many watersheds worldwide are already subject to a range of abrupt and gradual perturbations, including drought, floods, changes in timing and magnitude of snowmelt, and evolving temperature and precipitation patterns. While these changes are expected to have profound implications on water availability and quality for the downstream needs of ecosystems, energy and agricultural systems, and populations, the capabilities for accurately predicting how watersheds will respond to increasingly frequent perturbations are still in early stages of development.

Key challenges to predicting an aggregated signature of watershed discharge or water quality include the multi-scale biotic-abiotic interactions spanning from bedrock to canopy, including the saturated and unsaturated subsurface, soils and vegetation compartments, between terrestrial-aquatic subsystems, and along significant environmental gradients that often exist in watersheds. Better information is also needed regarding the range of future hydroclimate conditions and the stresses they place on natural water systems. A central challenge is the ability to couple physically-based modeling of the hydroclimate with watershed-scale observations and predictions.

5-YEAR GOALS

- Develop and integrate new modeling capabilities, process insights, and genome-to-satellite datasets to document how hydrological forcings, such as early snowmelt, influence water discharge
- Identify the mechanistic roles of microbes and plants in cycling water and nutrients and discover how hydrological forcings alter biogeochemical-ecological interactions and the flux of nutrients along watershed gradients from bedrock to canopy
- Develop scale-adaptive watershed reactive transport simulation capabilities that use Adaptive Mesh Refinement to zoom into specific watershed regions and predict fine-scale processes when and where they are likely to influence larger-scale behavior and cumulative water responses

10-YEAR GOALS

- Couple scale-adaptive hydroclimate, watershed, and hydrology simulation approaches to enable prediction of hydrologic phenomena and variability for all phases of water and at all stages in the water cycle
- Determine when and where new information significantly improves prediction of watershed responses to perturbations, and document the factors which must be included in operational forecasting models to enable science-based, near-time management decisions for water resiliency

2 Develop a water science knowledge-base that offers new analytical tools for decision-making

A critical gap in water resiliency is the ability to provide timely and predictive insights about the status of water distribution and quality to water utilities, end users, and decision-makers who must be informed about how to respond to current and future water challenges.

Advances in remote sensing, autonomous above- and below-ground sensor networks, and other observational tools have produced an explosion in data that describe water systems in greater spatial and temporal detail than ever before. We are continuing to develop the necessary tools that can translate these large, complex and diverse datasets, and combine them with socio-economic analyses into actionable water information. The challenges in harnessing the vast availability of big and diverse water data are in merging the heterogeneous datasets streaming from observations with model simulations, and ensuring the consistency of data quality.

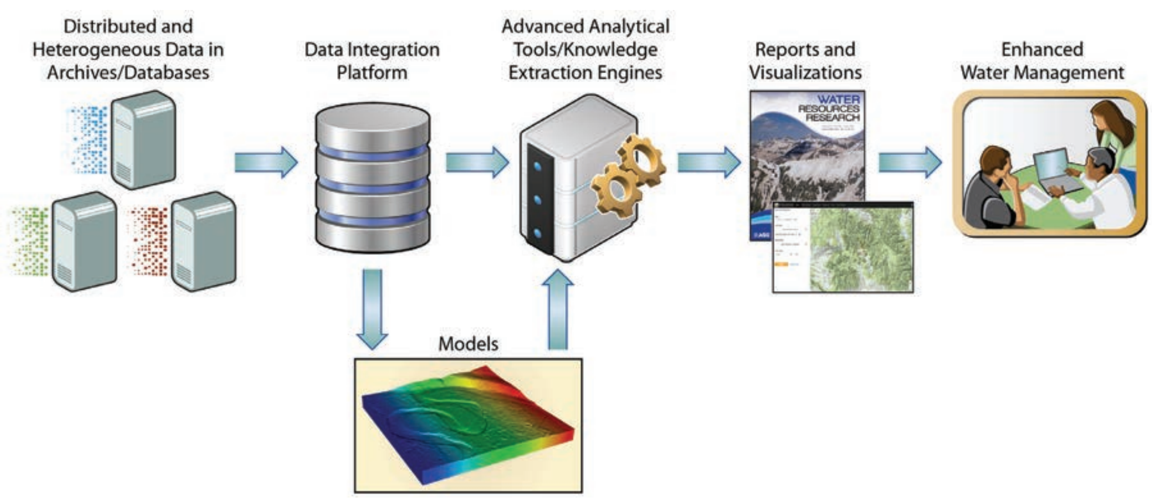
Field observations can include water distribution data on precipitation and snowpack, terrestrial baseflows, groundwater levels and quality, and other key environmental variables such as temperature and humidity. Simulations that project future water behavior include modeling across scales, interactions of coupled processes, and quantifying perturbation risk and event probabilities. Developing useful water data tools requires asking the right user-inspired questions and identifying the information gaps that must be addressed for optimizing water resource management decisions.

5-YEAR GOALS

- Design the data architecture and components of an advanced water knowledge-base platform that can assimilate increasingly complex, autonomous and massive streaming environmental datasets from diverse sources using statistical and machine learning algorithms capable of identifying critical system transitions and interactions
- Develop and validate the reliability of platform data components for near-time analysis and decision-making, and initiate the development of user-determined priority cases through partnerships with water agencies, big data initiatives and scientific partners
- Develop a conceptual and numeric framework for the simultaneous consideration of embedded energy in water and embedded water in energy that can inform management of the existing systems as well as future development scenarios

10-YEAR GOALS

- Incorporate new deep learning and other data tools into an integrated modeling and analysis water knowledge-base platform, and demonstrate its capability for informing water stakeholder decisions for a specific set of locally-relevant water use and climate scenarios
- Expand the knowledge-base platform to allow system-level assessment of linkages beyond water and climate, such as with energy policy and other socio-economic drivers, and expand its geographic applicability



DATA ANALYTICS FOR WATER RESOURCES

Integrating and analyzing water datasets using advanced data science capabilities can transform our ability to manage and predict changes to water resources.

3 Advance the scientific underpinning of new water management and treatment techniques

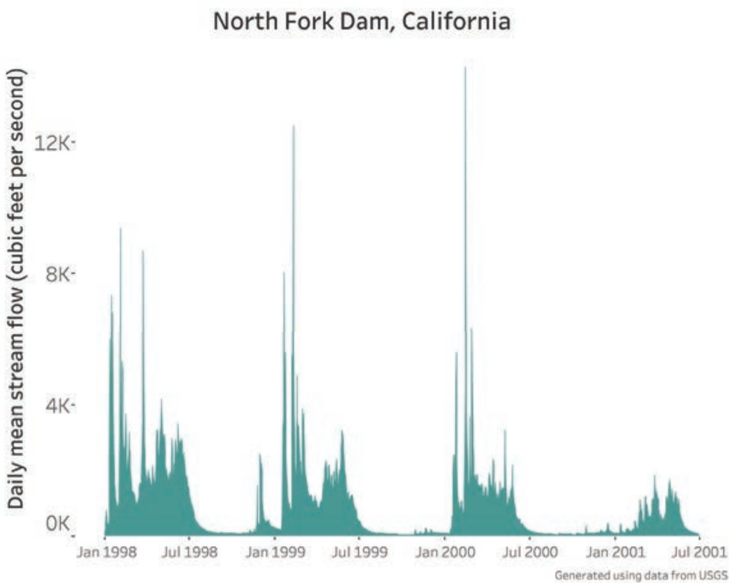
Another key aspect of water resiliency is the ability to efficiently store water, delivered through precipitation, as groundwater in the subsurface, and to be able to retrieve it where and when needed with assurance that its quality meets the desired use. Effective management of groundwater resources is limited in part by the ability to quantify and predict the physical, chemical, and biological dynamics affecting water in subsurface sediments. Using California as a testbed, Berkeley Lab is advancing the application of subsurface imaging and modeling toward developing scalable solutions for groundwater management.

On the surface, activities such as intensive agriculture can greatly impact subsurface water quality through the release of harmful contaminants, including nitrates. Below the surface, the depletion of groundwater aquifers causes serious land subsidence, compromising built infrastructure above ground or aquifer viability. Deep knowledge of aquifer function and response will allow more effective conjunctive use of groundwater resources and minimize energy demands of integrated water system operations.

Where water is not naturally available, new treatment and management methods can allow for beneficial reuse of non-traditional water sources, such as brines and produced water from subsurface energy and storage operations. With an understanding of the chemical composition of new geologic, industrial, or municipal water sources, non-traditional water can be matched with treatment approaches, such as desalination or managed 'reactive' aquifers. Such beneficial treatment options will increase water resiliency by bringing new water sources online for irrigation, groundwater recharge, or other industrial applications, while improving the sustainability of subsurface operations.

GROUNDWATER RECHARGE

Berkeley Lab is working with industry and academic partners to develop new sustainable groundwater management practices that can recharge groundwater aquifers in wet years. We are applying science to guide use of excess rainwater and snowmelt to flood crop lands and infiltrate water into aquifers deep underground, where it can be stored and redrawn during the irrigation season. Using almond orchards as a groundwater field observatory, teams of scientists and farmers are collecting experimental data that will increase the understanding of how and when to apply excess water and its effects on crop productivity, how water quality changes as it moves through the earth, and how and where the water can be recovered and reused.



HYDROCLIMATE WATER DELIVERY

This data illustrates the highly variable timing and magnitude of hydroclimate water delivery. Knowledge about water delivery improves preparation for events such as floods and droughts, but also maximizes beneficial use of available water, such as for groundwater recharge.

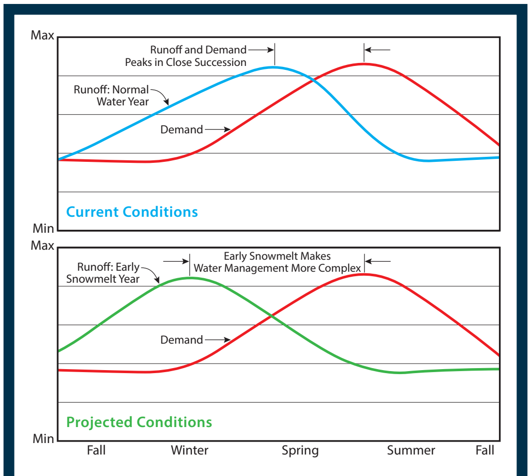
5-YEAR GOALS

- Instrument and monitor two groundwater recharge basin sites to yield geophysical imaging, modeling and wellbore data for estimating subsurface water recharge capacity for purposeful water infiltration
- Demonstrate at the same basin sites the ability to quantify the influence of subsurface transport and biogeochemistry on water quality dynamics by measuring the dissolution and precipitation of minerals, the accumulation of salts, and the release or uptake of trace metals
- Bring new specific produced water and brine management applications online using abiotic and biotic treatment technologies, and demonstrate their potential for beneficial reuse

10-YEAR GOALS

- Become a leading source of scientific and technical expertise and solutions for groundwater management and beneficial treatment and reuse of unconventional water by integrating these approaches into large-scale community field observatories

4 Demonstrate the ability to scale developed approaches for application in natural and intensively managed water systems



WATER MANAGEMENT

The curves show the general shape and timing of runoff and demand in California (individual watersheds each have unique characteristics). Much of the difference between high runoff and low demand in fall and winter can be captured and stored in the state's existing surface and groundwater storage facilities. That storage meets most of the demands later in spring and summer, and shortages are minimal. Adapted from California Water Plan, 2013.

Berkeley Lab's approach to resilient water systems will take advantage of field testbeds and community observatories. These testbeds will permit investigation of specific water challenges by pairing them to integrated scientific approaches that track and predict the complex physical, biological and chemical interactions influencing water management decisions.
The carefully selected sites will act as water observatories for studying a sub-region under the authority of local water utilities seeking to enhance water sustainability and resiliency. At the site, we can study the system response to a significant change in conditions or management practice. For example, treating non-traditional water for its application to groundwater banking on agricultural land in a region with severely depleted water tables. The testbeds will use measurements of water quality, location and movement to validate the predictions of models and evaluate the effectiveness of new approaches and technologies.

Successful testbed demonstrations from multiple sites will be used to build a predictive understanding of the water system at larger spatial scales. This predictive capability will include coupling between the natural and managed components of the water system, and impacts of water system management on energy consumption. Berkeley Lab will continue building a program in groundwater science that integrates capabilities in engineering, geophysics, hydrology, ecology, and biogeochemistry, and establish project sites in California and other regions that integrate science from subsurface characterizations including geochemical measurements, and hydrological, mechanical and chemical modeling.

5-YEAR GOALS

- Move select pilot-scale community testbeds into large-scale data collection, analysis, and application observatories, and develop a groundwater management package that integrates local and regional multi-scale field measurements and modeling data into tools for water management and risk analysis

10-YEAR GOALS

- Translate scientifically-proven solutions into options for informing new water resiliency policies and strategies that are co-managed by water authorities and stakeholders at the local, state and federal level

SELECT PROJECTS, FOUNDATIONAL SPONSORS & PARTNERS

PROJECTS

Almond Board of California Groundwater Recharge Project
Advanced Scientific Computing for Environmental Management
Brine Extraction Storage Test (BEST) Project
Clean Energy Research Center for Water-Energy Technologies (CERC-WET)
Hydraulic Fracturing Water Impacts
Hyporheic Zone Process Control on Riverbank Infiltration
Fukushima Research Projects
Interoperable Design of Extreme-scale Application Software (IDEAS)
Watershed Function Scientific Focus Area
Water Recharge at Scale LDRD
Water Resiliency for California Disadvantaged Communities

SPONSORS

DOE Office of Science, Biological and Environmental Research (BER)
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DOE Office of Environmental Management (EM)
DOE Office of Legacy Management (LM)
Army Corps of Engineers
California Energy Commission
California Natural Resources Agency
Almond Board of California
California Council on Science and Technology
Sonoma County Water Agency
University of California Office of the President (UCOP)
Bureau of Land Management
Environmental Protection Agency
California Department of Conservation
California Department of Water Resources
City of Berkeley
East Bay Municipal Utility District (EBMUD)
San Francisco Public Utilities Commission (SFPUC)
State Water Resources Control Board
South Kern Irrigation District

PARTNERS

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Berkeley Lab Energy Sciences Area
Berkeley Lab Energy Technologies Area
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Los Alamos National Laboratory (LANL)
National Renewable Energy Laboratory (NREL)
Pacific Northwest National Laboratory (PNNL)
Advanced Light Source
National Energy Research Scientific Computing Center (NERSC)
Molecular Foundry
UC Davis

04. SUSTAINABLE EARTH
SMARTER USE OF **SUBSURFACE RESOURCES**

THE CHALLENGE

Subsurface resources, which currently supply over 80% of the United States' energy needs, have enormous importance to our economy, jobs, and energy security. A large fraction of these energy needs is provided by fossil fuels, which when consumed release long-stored carbon into the atmosphere, with disruptive climatic effects. The transition to a large-scale U.S. clean energy future is expected to take decades, and may take longer in many other parts of the world. During this transition, new scientific discoveries and technological advances must enable smarter, cleaner, and more efficient and environmentally responsible use of subsurface resources. Advanced hydrocarbon production technologies can reduce environmental impacts, and, when coupled to large-scale geologic carbon sequestration, decrease the carbon footprint of fossil-based electricity. Geothermal heat mining can generate a tremendous amount of energy that is largely untapped today. The subsurface can also store large amounts of energy from intermittent renewable sources, and allow for the safe disposal of hazardous materials such as nuclear energy wastes.

Using subsurface resources also presents environmental challenges. For example, expansion of geothermal resources requires the creation of rock fractures and injection of fluids, which are a potential cause of induced seismicity. The possibility for groundwater contamination from deeper subsurface operations is also a concern. Developing smarter strategies that jointly address our major energy and environmental challenges requires greatly improved understanding of subsurface hydrological, geochemical, and geomechanical processes. This will allow us to evolve from 'trial-and-error' practices to applying 'adaptive control'. New approaches will rapidly monitor, predict, and provide access to subsurface resources while reducing environmental and economic risk.

OUTCOME

Achieving adaptive control of Earth's complex subsurface requires dramatic improvements in our ability to measure and influence processes underground. These capabilities will bring about major advances in cleaner and safer energy production and storage, improve our long-term energy security, and ensure the highest possible environmental responsibility. We will be able to realize a significant increase in geothermal resources, transition effectively to a clean energy future by pairing fossil energy use with carbon sequestration, ensure that groundwater is protected from contamination, and advance safe and cost-effective solutions to large-scale utilization of the subsurface. As new renewable energy sources come online, the subsurface will continue to be a critical resource that contributes to our societal well-being.

WHY BERKELEY LAB?

For over forty years, Berkeley Lab researchers have been at the leading edge of subsurface energy sciences. Today, as an important contributor to the renewable energy transition, Berkeley Lab is committed to reimagining how to access subsurface resources, and how to develop cleaner, more cost-effective and environmentally safe operations. Our fundamental science focuses on understanding the phenomena that occur between subsurface rocks and fluids from nanometer to pore to kilometer length scales. We couple fundamental theories about the interplay of belowground processes with new geophysical visualization methods, and apply them to build monitoring tools and test predictive capabilities that improve use of subsurface resources.

With an applied research portfolio in geological carbon sequestration, geothermal energy, hydrocarbon resources, nuclear waste disposal, and subsurface energy storage, Berkeley Lab can tackle the most pressing cross-cutting subsurface challenges, and develop methods that apply broadly and can be deployed at large-scale.

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CAN WE SIGNIFICANTLY REDUCE THE WATER AND ENVIRONMENTAL FOOTPRINT OF FOSSIL FUEL PRODUCTION AND USE?

CAN GEOTHERMAL ENERGY BE EXPANDED 100-FOLD TO BECOME A MAJOR PIECE OF THE NATIONAL ENERGY PORTFOLIO?

WILL COMMERCIAL-SCALE CARBON SEQUESTRATION BECOME TECHNICALLY AND ECONOMICALLY VIABLE AS A MEANS FOR REDUCING GREENHOUSE GAS EMISSIONS?

CAN WE DEVELOP DEEP SUBSURFACE ENERGY STORAGE TO ALLOW GREATER USE OF RENEWABLES SUCH AS WIND AND SOLAR?

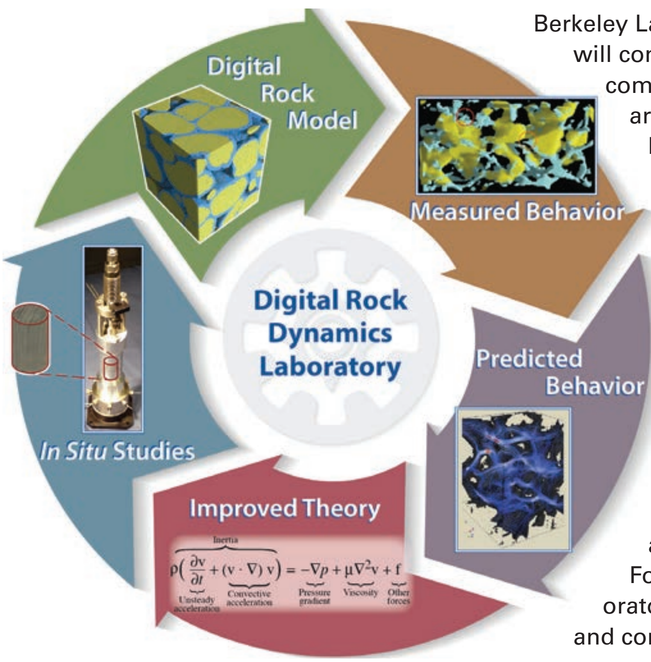
FOUR STRATEGIC RESEARCH OBJECTIVES

THE **GRAND** CHALLENGE

Demonstrate 'adaptive control' of subsurface reactions, mechanics, and fluid flow that improve environmental sustainability of energy recovery and storage applications at scale

1 Discover new fundamental descriptions of subsurface processes

Fundamental research provides the bedrock for understanding, modeling, and eventually influencing the behavior of subsurface phenomena in beneficial ways. Berkeley Lab researchers work at a range of spatial and temporal scales to discover the key relationships between Earth components that provide the most robust models of complex system behavior. For decades, these new insights have been captured, published and incorporated in powerful geoscience tools, such as multi-scale simulators of geophysical, geochemical and biogeochemical processes—but significant challenges remain.



Berkeley Lab's priority research directions have three overarching themes. First, we will continue our significant cross-disciplinary effort to better understand how complex processes, such as chemical reaction, rock mechanics and seismicity, are coupled. These coupled processes can cause non-linear evolution in rock behavior that must be tamed or guided for effective subsurface operations. A second strong emphasis will be on the establishment of new acoustic, electromagnetic, chemical or isotopic signatures of important subsurface events and processes. Such signatures are particularly vital for the development of time-lapse geophysics tools for real-time monitoring of field-scale processes.

Finally, through both laboratory and field activities we will develop new expertise to integrate diverse information types, such as imaging data and molecular simulation. Along with these activities, we will continue to develop innovative uses of high-performance computing, X-ray and neutron sources, and electron microscopy at facilities available in the DOE complex, complemented by in-house resources for stable isotope analyses, a wealth of characterization methods, and advanced engineering. For realizing progress on these priority tasks we seek to establish a new laboratory, the Digital Rock Dynamics Lab, to serve as an integrated experimental and computational analysis center for subsurface science.

DIGITAL ROCK DYNAMICS LABORATORY

Berkeley Lab proposes to establish the Digital Rock Dynamics Laboratory—a 21st century facility that serves as an integrated experimental and computational analysis center for subsurface science. The Digital Rock Dynamics Laboratory will comprise a suite of experimental and analytical geoscience resources that will greatly improve our ability to predict subsurface processes using high-fidelity digital models of rock-fluid dynamics (as shown on the opposite page) and other processes relevant to subsurface systems.

5-YEAR GOALS

- Establish a Digital Rock Dynamics Lab, which can serve as an integrated experimental and computational analysis center for subsurface science
- Build a more complete physical understanding of fluid flow, damage, and stress in the subsurface using new imaging and inversion approaches
- Develop predictive models of ion and molecule transport through nanoporous clay-rich materials at molecular and meso-scales, and measure and interpret non-equilibrium partitioning of isotopes and trace elements during mineral growth at low and high temperatures

10-YEAR GOALS

- Develop new methods for geophysical imaging of subsurface perturbations on timescales rapid enough to be used for real-time field scale monitoring and adaptive control of subsurface utilization
- Identify and incorporate into predictive models the geochemical processes that influence the behavior of stressed rock and subsurface permeability, including an integrated description of deformation and permeability change of clay-rich materials

2 Develop adaptive subsurface control strategies

Berkeley Lab excels at developing new sensing and measurement techniques to monitor subsurface processes within naturally heterogeneous rock formations. These capabilities offer the possibility of receiving information on subsurface system behavior quickly enough to allow for real-time or near real-time operational decisions during the manipulation of subsurface conditions, properties, and flow processes. The development of nimble, adaptive subsurface control strategies will greatly improve our ability to make use of subsurface resources with reduced environmental impact. These strategies will improve our ability to control where and when rocks are fractured to enable fluid flow, and to optimize the lifetimes of aquifers for the extraction or injection of substances.

The development of adaptive control approaches will require research in three areas. First, improved geophysical monitoring at higher spatial and temporal resolution will aid all subsurface operations. Second, the development of new sensors for physical, chemical and biological processes will enrich our ability to identify the key factors altering subsurface evolution. Third, ultra-fast simulation capabilities are needed for rapid processing and interpretation of measurements taken over nanometer to kilometer scales. Together, these advances will allow for rapid-response control and optimization of subsurface operations.

5-YEAR GOALS

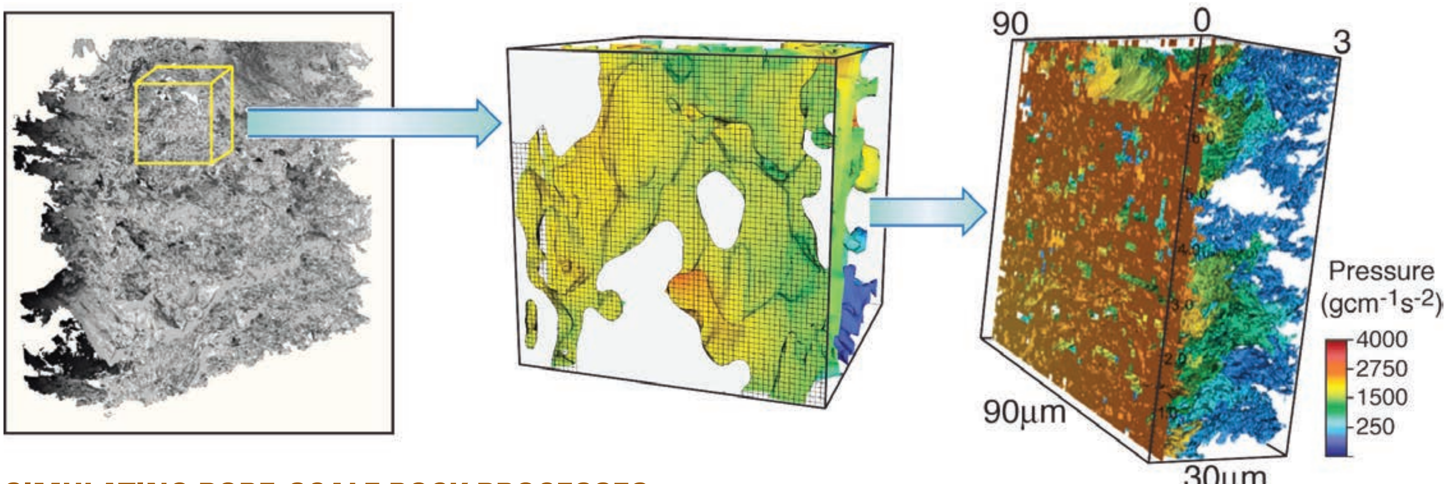
- Develop and integrate monitoring, analyses, and simulation capabilities that are accurate and fast enough to enable rapid-response adaptive control of subsurface processes
- Demonstrate integrated strategies for adaptive control in pilot applications

10-YEAR GOALS

- Use advanced sensor networks, exascale computing with scale-adaptive methods, and engineered control of coupled subsurface processes to guide select large-scale demonstrations involving adaptive control of subsurface processes

TESTING NEAR REAL-TIME MONITORING

In 2016, Berkeley Lab and collaborators carried out stress measurements and fracture stimulations at the SURF deep mine research facility in South Dakota. The project, called kISMET (which stands for permeability (*k*) and Induced Seismicity Management for Energy Technologies), drilled five vertical boreholes from a depth of 4850 feet, which were used to perform hydraulic fracturing. Continuous Active Source Seismic Monitoring (CASSM) and Electrical Resistivity Tomography (ERT) were used in boreholes proximal to the fracturing to test novel, near real-time monitoring techniques—a prerequisite for adaptive subsurface control. The kISMET site is attracting attention for similar studies that will further develop near real-time monitoring and imaging technologies for the deep subsurface.

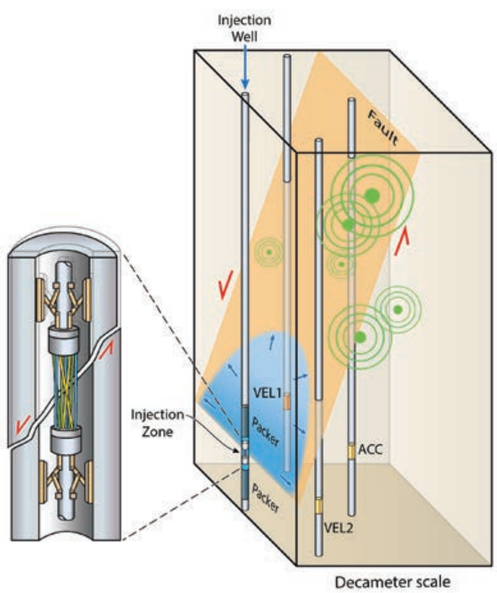


SIMULATING PORE-SCALE ROCK PROCESSES

The integration of experiment and analysis tests our ability to predict subsurface processes such as CO_2 sequestration or fluid flow through shale rock. From left to right, the coupled high-resolution 3D imaging, generation of a digital rock model, and simulation of fluid flow represents the state-of-the-art prediction of the properties of a rock with very low permeability.

3 Develop field sites and observatories that test enhanced techniques for energy production and storage at scale

Advances in subsurface science and engineering requires integrating observations, theory, numerical models, laboratory testing, and, ultimately, field experimentation. Field experiments placed in appropriate geologic sites are needed for validating, understanding and refining new sensors, theories, models, and adaptive control strategies under real-world conditions and heterogeneity. These can lead to unexpected outcomes not predicted by theory or laboratory work. Designated field observatories for subsurface science will enable research groups and industry stakeholders to test new methods and techniques.



PROBING AT THE SOURCE OF INDUCED SEISMICITY

How do subsurface operations induce seismicity? Induced earthquakes are typically studied remotely and away from the source zone, or in the laboratory where high-pressure, high-temperature conditions can be replicated, but where the scale is much smaller than on real faults.

Berkeley Lab has pioneered a new experimental method that allows controlled fault slip experiments in the deep underground, providing an experimental window in the field that goes beyond what is possible in the laboratory. The method allows tracking the deformation and permeability evolution in a fault during fluid injection at high temporal and spatial resolution, and offers a new vantage on the physical processes that occur along a fault as it begins to slide.

Berkeley Lab's expertise across geophysics, hydrogeology, and other disciplines allows us to lead the establishment of community subsurface energy observatories, and engage partners from diverse research and academic groups and industry. These dedicated energy observatories will build and curate data collections that will inform new science-based improvements for energy production and storage. They will advance frontier applications to industrial deployment, spanning geothermal and fossil energy, carbon storage, and nuclear waste disposal.

5-YEAR GOALS

- Develop at least two multi-user U.S. field observatories, and perform associated site characterization and model development for geologic, hydrologic, geomechanical and other geophysical properties
- Initiate field-scale testing of improved energy production and storage strategies

10-YEAR GOALS

- Rigorously assess the effectiveness of new subsurface methods developed at national field observatories and translate the most effective approaches to U.S. energy industries

4 Reduce the environmental impacts of energy-related subsurface activities

Energy and fuel extraction and storage in the subsurface entail risks to the environment, the economy, and human health. For example, oil and gas production can contaminate freshwater resources or the atmosphere, and the subsurface disposal of brines from hydrocarbon extraction or CO_2 sequestration can induce new seismic activity. Protection of freshwater resources is a priority since hydrocarbon extraction can require large amounts of water and jeopardize water quality. Berkeley Lab researchers are working to quantitatively assess and reduce environmental risks in current operations and in the decades-long transition to cleaner energy sources.

Reducing the potential for environmental impacts requires a blend of science and analysis. Important research activities involve studying the potential for hazard and failure of new subsurface materials and operations, developing new processes and methods for health of system diagnostics and remediation, and demonstrating in dedicated field test sites how to detect failures and mitigate environmental impacts. Our research findings will inform the development of risk scenarios for specific subsurface applications, assessing the probability of each, and quantifying the adverse consequences using predictive modeling. These assessments will be developed into operational guidelines and best practices for minimizing environmental risk that consider natural and manmade hazards, and will inform the creation of industry regulations. For major events such as the Gulf of Mexico oil spill or Fukushima nuclear accident, developing 'environmental first response' protocols can make the difference between a local incident or an international environmental disaster.

5-YEAR GOALS

- Develop new imaging and simulation approaches with particular focus on observing and quantifying subsurface failure processes and their environmental impacts
- Use improved predictive understanding of failure and impact to develop quantitative risk assessments and uncertainty predictions
- Produce guidance and inform policies for minimizing environmental risk, and serve in scientific advisory roles to national and international disaster response efforts involving subsurface operation mishaps
- Carry out integrated field experiments that investigate the possible consequences and mitigation approaches for adverse energy-related events such as induced seismicity, well leakage, and other system failures

10-YEAR GOALS

- Develop and demonstrate effective operating principles for safe, environmentally sustainable, and efficient subsurface activities for select large-scale and intensive energy and storage operations such as geologic CO_2 sequestration, enhanced geothermal energy production, compressed gas energy storage, or the disposal of hazardous industrial wastes

SELECT PROJECTS, FOUNDATIONAL SPONSORS & PARTNERS

PROJECTS

Assessment of Induced Seismicity in California

BES Geochemistry, Geophysics and Isotopes Projects

Brine Extraction Storage Test (BEST) Project

CCSMR – CO_2 Storage Field Experiments

Clean Energy Research Center for Water-Energy Technologies (CERC-WET)

Chevron Center of Excellence

DECOVALEX Model Comparison for Coupled Processes

Enhanced Geothermal Systems Projects

Energy Frontier Research Center (EFRC): Nanoscale Controls on Geologic CO_2

Frontier Observatory for Research in Geothermal Energy (FORGE)

Fukushima Cesium Mitigation

Fundamental Geosciences R&D

Methane Hydrates Research

National Risk Assessment Program

Nuclear Waste Disposal: Argillite, Crystalline, and Salt Host Rocks

Flexible Load Geothermal Energy

Subsurface Exascale Project

Subsurface LDRDs

Unconventional/Shales Research

SPONSORS

DOE Office of Science, Basic Energy Sciences (BES)

DOE Office of Science, Advanced Scientific Computing Research (ASCR)

DOE Office of Fossil Energy (FE)

DOE Office of Nuclear Energy (NE)

DOE Office of Energy Efficiency and Renewable Energy (EERE)

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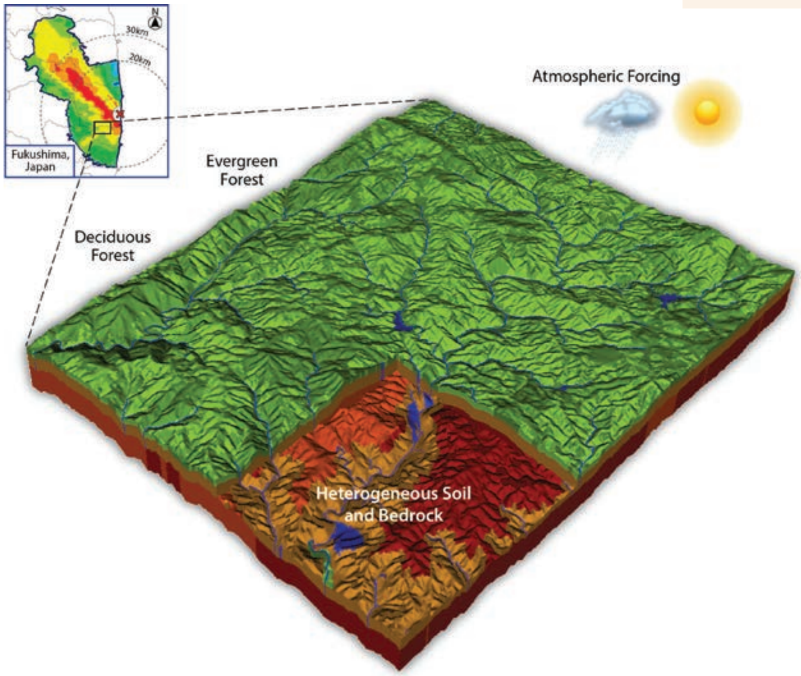
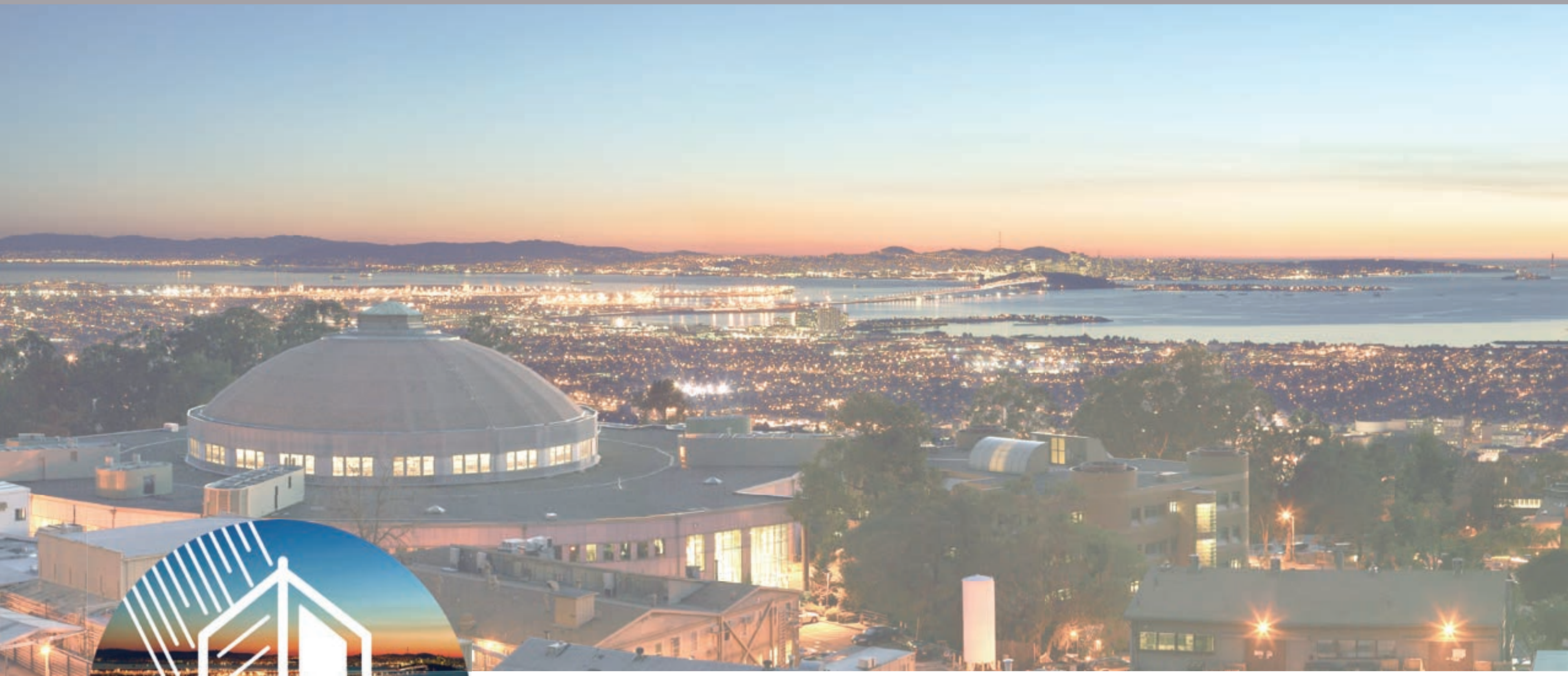


ENVIRONMENTAL PROTECTION AT FUKUSHIMA

Berkeley Lab has made significant contributions to environmental restoration in Japan following the Fukushima Nuclear Power Plant accident through advanced radioactive-source visualization technologies, multiscale integration and management of complex data sets, and predictive modeling of cesium transport in the environment. The figure shows a high-resolution groundwater-surface water model of a Fukushima watershed used to simulate the dynamics of the water-energy balance and predict Cs-137 transport and re-contamination due to erosion.



05. **RESILIENT SYSTEMS** STRATEGIES FOR **CRITICAL ENERGY, WATER** AND **BUILT SYSTEMS**

THE CHALLENGE

Over the next decades, worldwide increases in population and economic growth, coupled with climate change and natural hazards, will have tremendous impacts on the way of life for millions of people. Society must meet these challenges by seizing the numerous opportunities for adapting how it uses and manages limited natural resources. At the same time, we must ensure resilience of the built systems we depend on for energy, water, and critical infrastructure.

Our nation's systems—including cities, bridges, power plants, industrial complexes, and levees—were originally designed with the expectation that environmental conditions would remain within a fixed range of variability. Now resilient designs need to withstand both gradual and abrupt stresses, as well as address the added pressures of aging and urbanization. The current models used to design these systems must evolve into physically based, mechanistic models that provide high fidelity representations of critical systems under various conditions. These new models will test resilient system strategies to evaluate potentially catastrophic threats, consider a range of possible solutions, and discover associated risks and tradeoffs.

RESILIENT SYSTEMS
are those which maintain the ability to anticipate, prepare for, and adapt to changing conditions, and withstand, respond to, and recover rapidly from disruptions

Drawing on advances from the previously described grand challenges, new design paradigms can bridge the gap between simulation and observational capabilities to explicitly quantify and predict interactions between the natural, built and human system components. These interdisciplinary advances will inform engineering design, management decisions grounded in uncertainty quantification, scenario analytics, risk assessment, and other considerations necessary for minimizing future disruptions to our critical systems. Regional-scale case studies, test-beds, and engagement with stakeholders must play a central role in our efforts to understand and inform these challenges.

OUTCOME

INDEPENDENTLY MANAGED ENERGY, WATER AND BUILT SYSTEMS MUST TRANSITION TO STRATEGIES WHERE SYSTEM INTERDEPENDENCIES ARE CO-DESIGNED AND CO-MANAGED FOR INCREASED EFFICIENCY AND RESILIENCE

The increasing connectedness and complexity of critical systems exposes them to new risks from environmental and social changes but also creates new opportunities for improving their designs. Ultimately, this requires a coordinated effort among decision-makers, planners, engineers, and researchers to ask the right questions and to establish an evidence base that takes into account the natural and human interactions that will inform the assessments, capabilities, and frameworks necessary for improving system resilience. Using advanced modeling and sensing, the system designs of the future will maintain awareness of optimal operating conditions and potential for disruption, as well as a highly flexible capability to adapt in the face of diverse stresses.

WHY BERKELEY LAB?

Berkeley Lab has substantial capabilities to measure and predict many of the natural phenomena that pose some of the most severe threats to system resilience. We are exploring interactions between these natural phenomena and built system responses and system optimization. For example, Berkeley Lab is advancing new ways to simulate and observe climate phenomena (from gradual changes, such as sea-level rise, to fast-moving extremes, such as severe storms), the interactions of earthquake-induced strong ground motion with buildings, and the impacts of multiple stresses occurring simultaneously.

The advanced predictive capability for natural systems behavior is being coupled with models that can simulate critical built and human subsystems, characterize risk and performance responses to stress, and warn of the tipping points for catastrophic failure. Berkeley Lab's capabilities in nimble and networked sensing technologies add an active monitoring component to observing real-time system behavior. This brings models into real-world application and forms the basis for decision analysis tools that understand system interdependencies, the range of possible tradeoffs and uncertainties, and the risks associated with resource planning strategies.

CALIFORNIA AS A TESTBED FOR CLIMATE AND SEISMIC RESILIENCE

THE **GRAND** CHALLENGE

Develop and test disruption-ready strategies for resilience of critical energy, water, food and built infrastructure systems using advanced modeling and observational capabilities

The vulnerabilities of critical systems to changing climate extremes and seismic events are challenges faced in many regions and communities worldwide. As the sixth largest economy in the world and with a population that is projected to reach 42.5 million in 2025, California's vitality and prosperity are directly tied to aging infrastructure and its susceptibility to environmental and seismic threats. Berkeley Lab has a unique opportunity to develop and test resilient system solutions for California that could be widely applicable in other regions of the United States and the world.

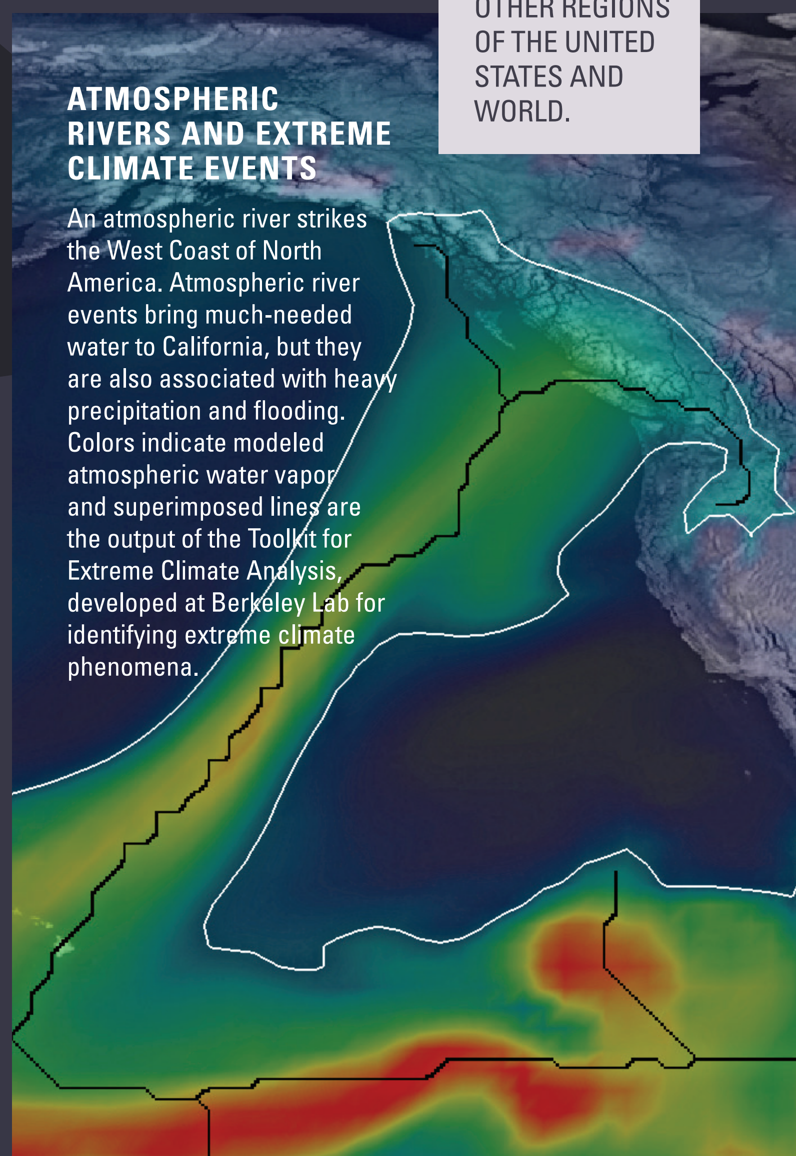
In particular, the San Francisco Bay Area provides an ideal starting point for considering solutions to these challenges. The city and its surroundings are undergoing rapid changes in demographics and economic disparity, yet it is a leading player in the global innovation economy and an early adopter of science and technology for addressing societal challenges. If any region is able to adequately prepare for and respond to these challenges, and serve as a model to be adopted in other regions, it should be the San Francisco Bay Area.

Like many regions, however, the San Francisco Bay Area faces multiple slow and fast-moving environmental challenges that were not anticipated just a few decades ago. The infrastructure of the region's cities are surrounded by coastline susceptible to sea-level rise, and the California drought is threatening the city's water supplies originating in the Eastern Sierra mountains. Drier and hotter temperatures are setting new records, and fueling fires in surrounding areas. Adding to these broad environmental challenges, the U.S. Geological Survey states that there is a 72% probability of at least one earthquake of magnitude 6.7 or greater striking somewhere in the San Francisco Bay Area before 2043.

> **"The state must also do more to protect critical infrastructure and plan for the impacts of climate change."**
>
> CALIFORNIA FIVE-YEAR INFRASTRUCTURE PLAN, 2016, OFFICE OF THE GOVERNOR

The San Francisco Bay Area is an ideal case study since it provides the opportunity to observe the interaction of many long-term climate, natural hazard, and infrastructure resiliency challenges faced by other regions around the world. For describing the strategic research objectives under Resilient Systems, we choose to focus on two high risk stressors to California: **CLIMATE** and **EARTHQUAKES**.

BERKELEY LAB HAS A UNIQUE OPPORTUNITY TO DEVELOP AND TEST RESILIENT SYSTEM SOLUTIONS FOR CALIFORNIA THAT COULD BE WIDELY APPLICABLE IN OTHER REGIONS OF THE UNITED STATES AND WORLD.



ATMOSPHERIC RIVERS AND EXTREME CLIMATE EVENTS

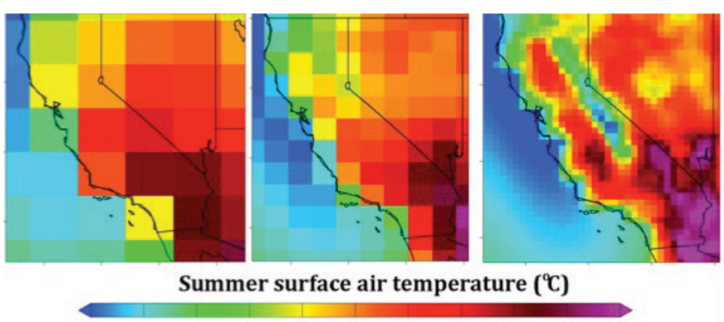
An atmospheric river strikes the West Coast of North America. Atmospheric river events bring much-needed water to California, but they are also associated with heavy precipitation and flooding. Colors indicate modeled atmospheric water vapor and superimposed lines are the output of the Toolkit for Extreme Climate Analysis, developed at Berkeley Lab for identifying extreme climate phenomena.

FOUR STRATEGIC RESEARCH OBJECTIVES

1 Develop a fundamental understanding of the principal stressors disrupting critical societal systems

Resilient system design relies on accurate prediction of the principal stressors that can disrupt societal systems. These can include acute stresses such as extreme weather, major earthquakes and tsunamis, or more gradual changes such as aging infrastructure, steady climate changes, and shifting resource demands.

High-resolution temporal and spatial modeling of projected climate changes will bring about a new fundamental understanding of how trends and extremes will impact specific regions. This ability requires the advanced computational methods that Berkeley Lab is developing for understanding, detecting and predicting the physical drivers of extreme weather events and the coupling of climate phenomena with the human and built environment. New physics-based simulations can also evaluate the site-specific nature of natural and induced earthquake ground motion and its coupling to built infrastructure. Using these advanced techniques, scientists will be able to provide credible predictions of anticipated stresses and associated risks, which will lead to improved management and design of new infrastructure.



SURFACE AIR TEMPERATURE High resolution modeling can accurately represent climate phenomena at the regional and local scales where water management, urban planning, and other decision are made. Shown here is the mean surface air temperature for the period 1979-2005 from three simulations at varying resolutions using the Community Atmosphere Model. Only the highest resolution simulation (25 km) differentiates important features in California, such the Central Valley and Sierra Nevada Mountains.

UNDERSTANDING URBAN CLIMATE STRESSES

5-YEAR GOALS

- Develop an urban hydroclimate modeling capability that simulates the range of expected temperatures, water stresses, and other extremes impacting a region's densest population areas
- Predict the impacts on regional water supplies from reduced winter snowpack in mountainous regions and increased ecosystem evapotranspiration
- Downscale global climate models to regional scales to provide estimates of sea level rise and storm surge in coastal zones
- Simulate kilometer-scale temperature gradients and energy usage across the San Francisco Bay Area during a major heat wave, including the effects of fog on ecological health

10-YEAR GOAL

- Systematically quantify the sources of uncertainty that limit our ability to predict the principal climate stressors facing major metropolitan regions of the United States, and identify the key model improvements necessary for narrowing these uncertainties

UNDERSTANDING SEISMIC STRESSES ON CRITICAL INFRASTRUCTURE

5-YEAR GOALS

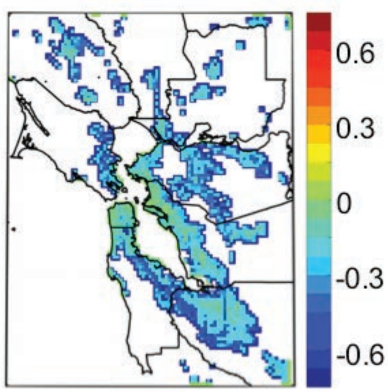
- Develop a suite of powerful earthquake ground motion simulators with advanced, high-performance geophysics wave propagation codes to perform parallel ground motion simulations of regional extent
- Produce substantially improved understanding of the distribution, amplitude and frequency of potential future earthquake motions with insight into how these motions will impact critical infrastructure
- Develop a regional-scale geophysics model of the San Francisco Bay Area that is capable of simulating the highest probability earthquake rupture scenarios and resulting ground motions at frequencies of engineering relevance

10-YEAR GOALS

- Quantify utility of advanced simulation methods for improving resiliency of built energy
- Establish a regional-scale transformational earthquake hazard and risk assessment for the San Francisco Bay Area and develop regional partnerships with key stakeholders from utilities, government and industry
- Apply methods developed for the San Francisco Bay Area to other seismically active regions around the globe

2 Characterize the limits of critical systems under current and changing stresses

With a more detailed picture of the stresses facing critical systems, quantitative modeling can simulate how the system will respond to environmental pressures or abrupt hazards, and identify tipping points that could lead to acute system failures or economic and other losses. Modeling the coupled human-natural system interactions can be used to understand the feedbacks from resource management systems to the environment. For example, simulating the interactions among regional climate, land-use patterns, and the electricity grid can reveal where energy and cooling demands will peak during a heat wave, as well as reveal opportunities where mitigation strategies, such as cooling roofs, will provide maximum benefit.



REDUCED IRRIGATION WATER (MM/DAY)

Modeling Urban Microclimate

Understanding how global climate change will impact energy, water, and built infrastructure in urban environments requires modeling capabilities that account for neighborhood-scale interactions among microclimate, the built environment, and landscape practices. Shown here is the potential for reduced landscape irrigation water use with widespread adoption of cool roofs in the San Francisco Bay Area.

Modeling can also predict how these impacts will be compounded when multiple stresses converge at the same time and place. Engaging stakeholders in generating user-inspired models is a key consideration for unpacking system behavior and being able to quantify key decision-relevant system parameters. For well-characterized systems, planners and engineers will need a description of system limitations within the range of expected environmental conditions that are necessary for guiding resilient system designs. For example, high performance computational capabilities for mechanistically simulating ground motion and infrastructure damage allow for hazard assessment of existing critical infrastructure and can lead to performance-based design of new critical facilities.

COASTAL FLOOD RISK

Coastal flood risk in the San Francisco Bay Area under a scenario of 1.25m sea level rise, combined with a 20-year storm surge event. Generated using the Our Coast Our Future Flood Map Tool.

CHARACTERIZING URBAN RESPONSES TO CLIMATE CHANGE

5-YEAR GOALS

- Model urban energy and water demand as a function of neighborhood-scale weather conditions, and investigate the role that urban land-use measures can play in reducing heat extremes, water demand, and flood risk
- Incorporate detailed representations of coastal infrastructure into emerging model-data systems that represent wave propagation, flooding, and ecosystem function in coastal zones

10-YEAR GOALS

- Build a leading urban hydrologic model that accounts for impervious surfaces and stormwater infrastructure at scales of 1–100 meters, and is capable of assessing flood risk to buildings and infrastructure in response to extreme precipitation and sea level rise

CHARACTERIZING INFRASTRUCTURE RESPONSES TO SEISMICITY

5-YEAR GOALS

- Create advanced models for the nonlinear seismic response of critical infrastructure that provide accurate quantitative estimates of structural damage and life safety risks for a range of ground motions
- Develop workflow for parallel ground motion simulations coupled with computational models of localized, near-surface soils and structural mechanics models of infrastructure
- Translate model results into risks by analyzing built infrastructure responses to simulated ground motions across the San Francisco Bay Area and other seismically active regions around the globe

10-YEAR GOALS

- Establish a multi-stakeholder partnership across regional transportation, energy, infrastructure and safety agencies, which will contribute to the building of the first high-performance hazard and risk computational model that describes probabilities for a large number of rupture and geologic scenario characterizations

3 Use transformative sensing technologies and data tools to monitor critical system behavior

Even with impressive improvements in spatial and temporal resolutions, computational models are not able to supply real-time information about actual environmental conditions and system performance. Berkeley Lab is pioneering nimble and networked sensing capabilities that will provide an unprecedented ability to measure the natural and built environment.

In subsurface sensing, for example, metering technology and fiber optic sensors can make physical measurements of various aspects of energy and water system dynamics and the condition of built infrastructure. Measurements of built infrastructure responses to earthquakes can be dramatically improved through the massive deployment of seismometers coupled to electric utility meters, or through distributed acoustic sensing using the large number of existing and unused underground fiber optic cables from excess telecom capacity.

In the air, Unmanned Aerial Systems offer entirely new digital measurement capabilities in optical, hyperspectral and thermal imaging. Storage, analyses and integration of the large datasets generated through these approaches create new challenges for ensuring data quality and provenance, and require high-performance computing and storage approaches capable of dealing with big data.

ENERGY AND WATER SYSTEM SENSING TECHNOLOGIES

5-YEAR GOALS

- Develop urban energy and water sensor packages, and work with stakeholders to integrate data into climate, hydrologic, and land-use modeling efforts

10-YEAR GOALS

- Develop stakeholder-informed data platforms and tools that can readily translate information across sources, sectors, and scales to inform both scientific investigation and regional planning and policy development

GROUND MOTION AND CRITICAL INFRASTRUCTURE SENSING TECHNOLOGIES

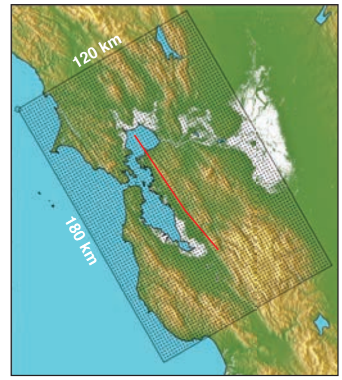
5-YEAR GOALS

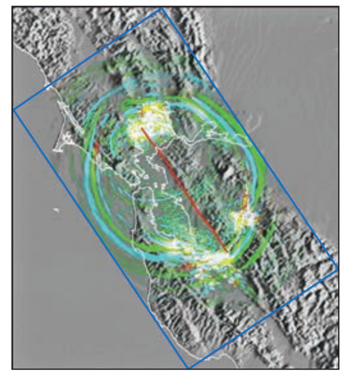
- Develop and test new approaches to large-scale distributed sensing of ground motion and infrastructure response
- Use distributed sensor data from frequent small earthquakes to develop and validate high-fidelity models of critical infrastructure that improve understanding of the safety margins required to protect against earthquake-induced failure at critical facilities
- Deploy an extensive array of earthquake sensors across the San Francisco Bay Area to sense nonlinear responses of infrastructure at extreme densities

10-YEAR GOALS

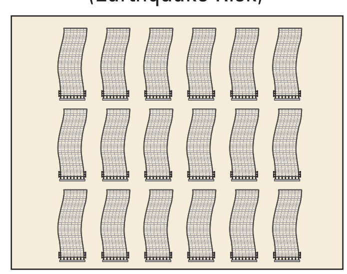
- Develop an integrated systems approach which combines high performance computational models and dense sensor data to reduce uncertainties and increase reliability in earthquake hazard prediction at fine scales

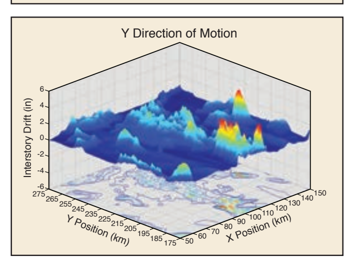
Ground Motion Simulation (Earthquake Hazard)





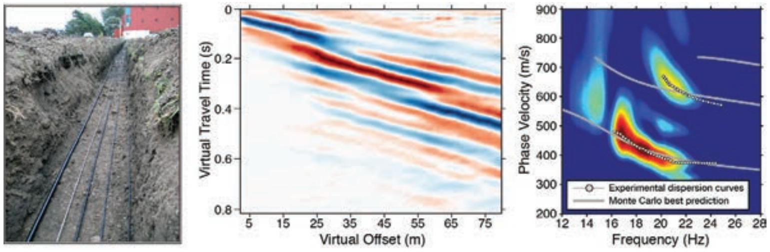
Building Simulations (Earthquake Risk)





SIMULATING GROUND MOTION AND RISK

Coupling regional-scale geophysics simulations of earthquake processes with engineering mechanics simulations of nonlinear structural response for a simultaneous regional estimate of earthquake hazard and risk to key facilities in the San Francisco Bay Area.



SUBSURFACE MONITORING WITH FIBER OPTICS

These images show fiber optic cables in a shallow trench (left), a resulting seismic dataset generated using infrastructure noise (center), and analysis of data for measuring near-surface seismic velocity (right)

4 Assess tradeoffs in efficiency, cost, risk, and reliability to inform resilient design of critical systems

Resilient system designs and management decisions need to be based on probabilistic risk-informed frameworks that assess the combined effects of climate change and other natural phenomena. This must be done in a manner that stakeholders readily access and use for societal benefit. For example, in an energy-constrained and uncertain climate future, authorities need the ability to quickly assess the range of possible utility-scale decision pathways available to them for effectively co-managing resources. Given the many relevant system interdependencies, ignoring the impacts of decisions about one resource can result in sub-optimal performance for another.

Integrated models that couple predictive simulations with real-time observations will greatly improve the ability to assess potential benefits and risks and optimize strategies for resource allocation. Berkeley Lab is developing the tools necessary for transforming large and complex information about critical systems into knowledge for decision-makers.

TRADEOFFS IN URBAN CLIMATE RESILIENCE

5-YEAR GOALS

- Engage stakeholders to inform research design and derive system-level metrics for evaluating the resiliency, reliability, costs and risks of alternative energy, water and infrastructure development pathways
- Develop prototype scenario analytics frameworks to assess the water, energy, and climate resilience implications of alternative land-use and infrastructure development pathways

10-YEAR GOALS

- Develop a scenario analytics and visualization framework that leverages modeling and data capabilities to inform the expected outcomes of multiple infrastructure development, land-use planning, technology, and design pathways on the evolution and resiliency of critical systems

TRADEOFFS IN INFRASTRUCTURE SEISMIC RESILIENCE

5-YEAR GOALS

- Translate the scientific understanding of seismic impacts on critical systems into a set of actionable engineering requirements and standards that guide the future design of more resilient and less costly infrastructure for the San Francisco Bay Area
- Engage stakeholders to ensure that emerging frameworks appropriately translate into design practices and decision-making processes at the level of city, county and state agencies responsible for critical system infrastructure

10-YEAR GOALS

- Promote successful outcomes through a national committee for engineering codes and standards that will define consensus-based procedures for using advanced simulations and assessments of hazard and risk in broader engineering design and analysis applications

SELECT PROJECTS, FOUNDATIONAL SPONSORS & PARTNERS

PROJECTS

A Modern Computational Framework for Seismic Analysis of Nuclear Facilities and Systems

CASCADE Scientific Focus Area

CERC-WEST

Critical Infrastructure

Exascale Regional Scale Seismic Hazard and Risk Assessments

Fiber Optic Deformation and Ground Motion Sensing

Fukushima Environmental Restoration Research

Hyperion Project

Optical Sensors for Rapid Assessment of Earthquake Response of Critical Facilities

Urban Water-Energy LDRD

SPONSORS

DOE Office of Science, Biological and Environmental Research

DOE Office of Science Advanced Scientific Computing Research

DOE Office of Nuclear Safety

California Energy Commission (CEC)

Japan Atomic Energy Agency Pacific Gas & Electric

PARTNERS

Bay Area Air Quality Management District (BAAQMD)

Bay Area Regional Health Inequities Initiative (BARHII)

Berkeley Lab Computing Sciences Area

Berkeley Lab Energy Technologies Area

Climate Readiness Institute (CRI)

Lawrence Livermore National Laboratory (LLNL)

National Energy Research Scientific Computing Center (NERSC)

Pacific Northwest National

Laboratory (PNNL)

San Francisco Bay Conservation and Development Commission (BCDC)

San Francisco Public Utilities Commission (SFPUC)

UC Davis

University of Nevada Reno

SELECT **EESA PROJECTS**, 2017

A Modern Computational Framework for Seismic Analysis of Nuclear Facilities and Systems

Accelerated Climate Modeling for Energy (ACME)

Advanced Scientific Computing for Environmental Management

Almond Board of California Groundwater Recharge Project

AmeriFlux Management Project

Application Software (IDEAS)

ARM Southern Great Plains and Carbon Project

Assessment of Induced Seismicity in California

Atmospheric System Research (ASR)

Belowground Carbon Cycling Scientific Focus Area

Berkeley Synchrotron Infrared Structural

BES Geochemistry, Geophysics and Isotopes Projects

Bioenergy Biology Projects (JBEI, LLNL Biofuels SFA, EBI)

Biogeochemical Cycle Feedbacks

Biogeochemistry-Climate and Soil Warming (BGC)

Biological and Environmental Program Integration Center (BioEPIC)

Biological Feedbacks Scientific Focus Area

Biology (BSISB) Program

Brine Extraction Storage Test (BEST) Project

Calibrated and Systematic Characterization, Attribution, & Detection of Extremes (CASCADE)

California Soil Carbon and Response to Drought Catalyst Award

CCSMR – CO_2 Storage Field Experiments

Chevron Center of Excellence

Clean Energy Research Center for Water-Energy Technologies (CERC-WET)

Critical Infrastructure

DECOVALEX Model Comparison for Coupled Processes

Ecosystems and Networks Integrated with Genes and Molecular Assemblies (ENIGMA)

Energy Frontier Research Center (EFRC): Nanoscale Controls on Geologic CO_2

Enhanced Geothermal Systems Projects

Exascale Regional Scale Seismic Hazard and Risk Assessments

Fiber Optic Deformation and Ground Motion Sensing

Flexible Load Geothermal Energy

Frontier Observatory for Research in Geothermal Energy (FORGE)

Fukushima Environmental Restoration Research

Fundamental Geosciences R&D

Hydraulic Fracturing Water Impacts

Hyperion Climate Decision Science

Hyporheic Zone Process Control on Riverbank Infiltration

International Land Model Benchmarking (ILAMB)

Interoperable Design of Extreme-scale Application Software (IDEAS)

Lighthouse

Marin Carbon Project

Methane Hydrates Research

Microbes-to-Biomes (M2B) LDRD

MULTISCALE

National Risk Assessment Program

Next Generation Ecosystem Experiments NGEE-Tropics & NGEE-Arctic

Nuclear Waste Disposal: Argillite, Crystalline, and Salt Host Rocks

Optical Sensors for Rapid Assessment of Earthquake Response of Critical Facilities

Research for Sustainable Bioenergy

Soil Carbon Management

SPRUCE (Spruce and Peatland Response Under Climatic and Environmental Change)

Subsurface Exascale Project

Subsurface LDRDs

Systems Biology of Carbon Cycling

Tomographic Electrical Rhizosphere Imaging (TERI)

UC Consortium for Drought and Carbon Management (UC DroCaM)

Unconventional/Shales Research

Urban Water-Energy LDRD

Water Recharge at Scale LDRD

Water Resiliency for California Disadvantaged Communities

Watershed Function Scientific Focus Area

SELECT **EESA SPONSORS, PARTNERS, AND RESOURCES**

DEPARTMENT OF ENERGY

Office of Science, Biological and Environmental Research (BER)

Office of Science, Basic Energy Sciences (BES)

Office of Science, Advanced Scientific Computing Research (ASCR)

Office of Energy Efficiency and Renewable Energy (EERE)

Office of Environmental Management (EM)

Office of Fossil Energy (FE)

Office of Legacy Management (LM)

Office of Nuclear Energy (NE)

Office of Nuclear Safety (NS)

Advanced Research Projects Agency-Energy (ARPA-E)

SELECT OTHER SPONSORS

Almond Board of California

Army Corps of Engineers

Bureau of Land Management

California Council on Science and Technology (CCST)

California Department of Conservation

California Department of Water Resources

California Energy Commission (CEC)

California EPA Air Resources Board

California Natural Resources Agency

Calpine Corporation

Chevron Corporation

City of Berkeley

East Bay Municipal Utility District (EBMUD)

Electric Power Research Institute

Energy Biosciences Institute (EBI)

Environmental Protection Agency

Japan Atomic Energy Agency

Korea Atomic Energy Research Institute

National Aeronautics and Space Administration (NASA)

National Institute of Health (NIH)

National Oceanic and Atmospheric Administration (NOAA)

National Science Foundation (NSF)

Ormat Technologies, Inc.

Pacific Gas & Electric

San Francisco Public Utilities Commission (SFPUC)

Saudi Aramco

Sonoma County Water Agency

South Kern Irrigation District

State Water Resources Control Board

Total Global

U.S. Environmental Protection Agency

University of California Office of the President (UCOP)

BERKELEY LAB AREA PARTNERS

Biosciences Area

Computing Sciences Area

Energy Sciences Area

Energy Technologies Area

Physical Sciences Area

DOE NATIONAL LAB PARTNERS

Argonne National Laboratory (ANL)

Brookhaven National Laboratory (BNL)

Idaho National Laboratory (INL)

Lawrence Livermore National Laboratory (LLNL)

Los Alamos National Laboratory (LANL)

National Energy Technology Laboratory (NETL)

National Renewable Energy Laboratory (NREL)

Oak Ridge National Laboratory (ORNL)

Pacific Northwest National Laboratory (PNNL)

Sandia National Laboratories (SNL)

Savannah River National Laboratory (SRNL)

SLAC National Accelerator Laboratory

DOE USER FACILITIES AT BERKELEY LAB

Advanced Light Source

Joint Genome Institute (JGI)

National Energy Research Scientific Computing Center (NERSC)

National Center for Electron Microscopy (NCEM)

Molecular Foundry

CROSS-CUTTING TECHNOLOGIES & PLATFORMS

To enable several of the Grand Challenges, EESA has set a goal of developing three agile and highly-configurable Cross-cutting Technologies & Platforms:

- **COMMUNITY OBSERVATORIES**
- **NIMBLE & NETWORKED SENSING SYSTEMS**
- **SCALE-ADAPTIVE DATA & SIMULATION TOOLS**

When developed and used in combination, this suite of capabilities will provide a seamless ability to observe and simulate *in situ* dynamic processes across vast spatial and temporal scales.

AERIAL AND GROUND-BASED OBSERVATIONS

The explosion in environmental 'big data' promises to profoundly improve our understanding of climate and human-induced impacts on the environment.

COMMUNITY OBSERVATORIES

Like many scientific endeavors, earth and environmental research is advanced by integration of theory, observations and numerical models. However, unlike scientific fields where investigations can be sufficiently explored in the laboratory, it is critically important to test earth and environmental science theory and approaches in the field—under *in situ* real-world conditions, across compartments and scales, and in the presence of natural gradients and forcings.

It is critically important to test earth and environmental science theory and approaches in the field—under *in situ* real-world conditions, across compartments and scales, and in the presence of natural conditions.

We prioritize the development of community observatories as a cross-cutting technology platform because field testing is critical to meeting and integrating the EESA Grand Challenges. Community observatories are long-term earth and environmental research sites that allow critical observations to be made across a range of relevant Earth system compartments—from deep bedrock to the atmosphere—across natural gradients and lithologic regions, and from sub-second to multi-decadal timescales.

Community observatories provide important instrument and technology testbeds, and facilitate the acquisition of continuous, large and diverse datasets that can be used to study long-term behavior of natural systems. These observatory sites can also be used to manipulate or perturb the system and study its responses. Importantly, community observatories offer a platform for stakeholder collaboration across different disciplines and institutions, often driven by a common scientific challenge.

NIMBLE & NETWORKED SENSING SYSTEMS

Acquiring *in situ* measurements by using nimble and networked sensing systems is key to the EESA Grand Challenges. Taking advantage of the 'Internet of Things' is transforming the way we observe natural systems. Nimble and networked sensing systems are being developed to quantify biogeochemical, hydrological, geomechanical, geological and atmospheric properties. These technologies can be configured as single-point measurement devices or as networked arrays that provide larger spatial coverage and higher sampling density.

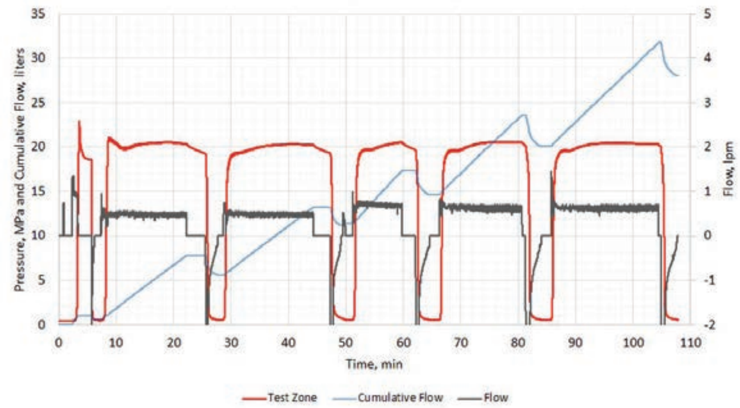
For example, autonomous unmanned aerial systems (UAS) are capable of carrying various sensor packages and imaging difficult-to-reach environments at high resolution. We are developing geophysical approaches to non-invasively sense a wide range of attributes governing Earth and environmental system behavior, from fracture formation in reservoirs to microbes near plant roots to cloud formation. We are using novel fiber-optic distributed sensors to autonomously measure subsurface temperature, strain, and acoustic signals, which in the future will potentially indicate changes in chemistry, radiation, and electromagnetic fields under ground.

In addition to advancing measurement techniques, another important aspect of this cross-cutting technology is to coincidently collect and integrate a wide range of different datasets across multiple sensor platforms. We envision that in the near future, EESA's suite of nimble and networked sensors can be routinely used to coincidentally monitor processes above- and below-ground. We anticipate that these approaches will greatly improve our insights into system behavior and our ability to rapidly detect critical system thresholds.

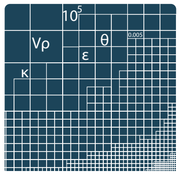
Currently, we are using such technologies to explore how Arctic ecosystems 'breathe,' how water 'flows' beneath our feet, how fracturing and stress induce microseismicity, and how CO_2 transforms as it migrates from deep reservoirs to shallower systems.

kISMET STIMULATION EXPERIMENT

kISMET pressure-flow experiment showing increased fluid pressure (red curve) used to cause rock fracture (blue curve) and fluid flow.



SCALE-ADAPTIVE DATA & SIMULATION TOOLS



A central impediment to progress on the EESA Grand Challenges is the currently limited ability to extract knowledge from wildly diverse sets of data for tractable prediction of multi-scale phenomena. With an increase in the use of autonomous sensing technologies and the resulting discovery of new mechanisms that drive complex interactions and feedbacks, the diversity of data is expected to increase.

Scale-adaptive data tools are new approaches that enable knowledge generation from diverse multi-scale data including deep machine learning and data analytics, new visualizations of complex, multi-scale spatial and temporal data, and approaches to rapidly perform parameter estimation using large observational datasets. Scale-adaptive simulation tools, such as Adaptive Mesh Refinement (AMR), are being used to allow models to 'telescope' into compartments of a system and change resolution and computational allocations when and where needed for improving prediction of multi-scale system behavior.

Several Grand Challenges will benefit from these capabilities, which are being developed alongside exascale computational capabilities. For example, modeling watershed function is an exascale problem that benefits from scale-adaptive capabilities, as simulation requires coupling water flow to small-scale biogeochemical and vegetation dynamics, all occurring within a heterogeneous environment and subject to extreme hydrological perturbations, such as floods or droughts.

In the subsurface, scale-adaptive approaches can improve simulation of the geochemical evolution of a deep fracture system that potentially impacts geological sequestration caprock integrity, as it necessitates prediction of reservoir behavior at 1-km length scales informed by micron-scale features and processes.

For climate predictions, scale-adaptive data and simulation are critical for detecting and tracking climate extreme event features, and for predicting the influence of localized extreme events on regional and global climate patterns. These data and simulation tools underpin our Grand Challenges and allow EESA scientists to address their critical underlying questions, such as identifying the minimum amount and type of information required to predict system behavior accurately enough to guide resilient energy and environmental management solutions.

kISMET OBSERVATORY

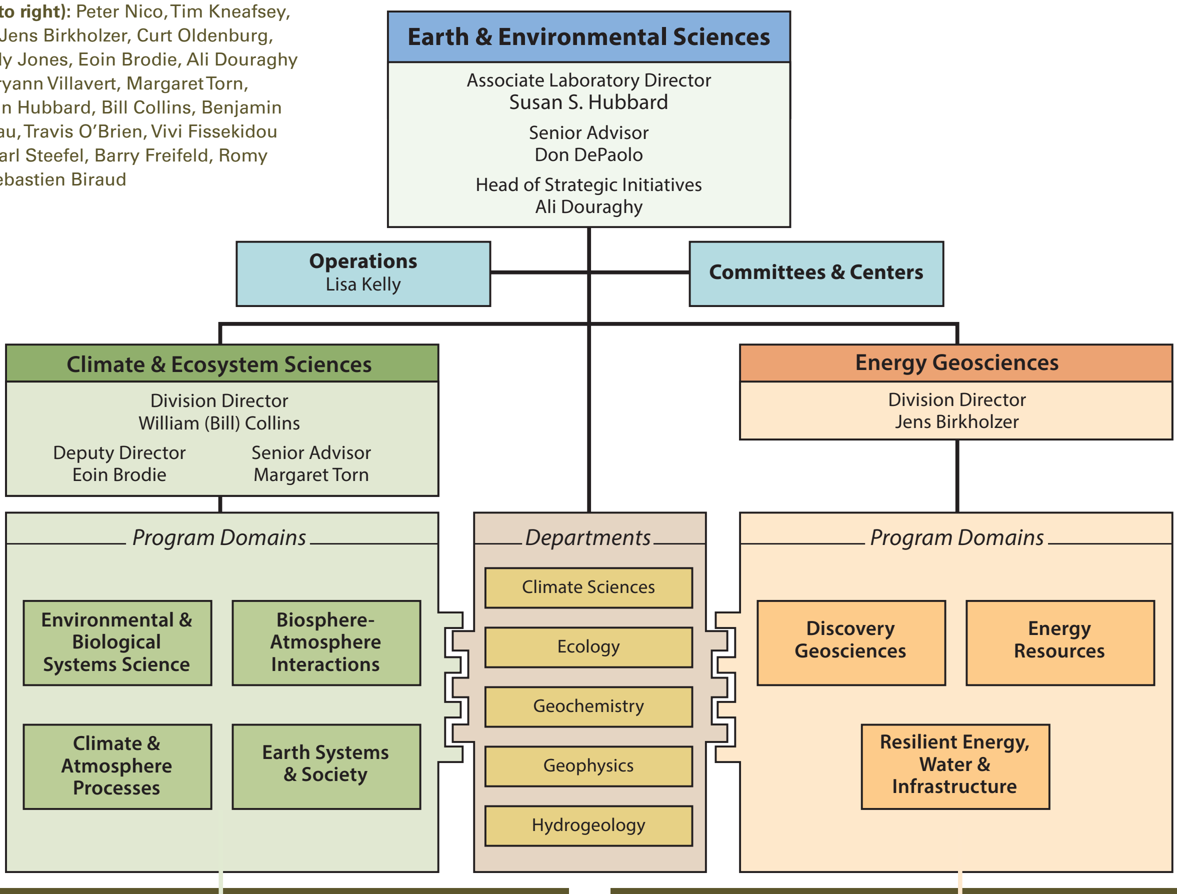
Permeability (k) and Induced Seismicity Management for Energy Technologies (kISMET) Observatory at the SURF deep mine research facility in South Dakota

EESA DIVISIONS

The breadth of expertise offered by the Climate and Ecosystem Sciences Division and the Energy Geosciences Division enables EESA scientists to address pressing environmental and energy challenges. Our Divisions advance and integrate diverse expertise to accelerate scientific discoveries and their translation into scalable solutions that sustain Earth's environment and the growing need for energy and water resources.

Area Council Leadership

Back Row (left to right): Peter Nico, Tim Kneafsey, Tracy Bigelow, Jens Birkholzer, Curt Oldenburg, Tom Daley, Andy Jones, Eoin Brodie, Ali Douraghy
Front Row: Maryann Villavert, Margaret Torn, Lisa Kelly, Susan Hubbard, Bill Collins, Benjamin Gilbert, Peter Lau, Travis O'Brien, Vivi Fissekidou
Not Pictured: Carl Steefel, Barry Freifeld, Romy Chakraborty, Sebastien Biraud



CLIMATE AND ECOSYSTEM SCIENCES DIVISION (CESD), led by William 'Bill' Collins, develops the foundational knowledge and capabilities needed to understand, predict, and advance stewardship of Earth's climate and ecosystems.

ENERGY GEOSCIENCES DIVISION (EGD), led by Jens Birkholzer, creates basic and use-inspired knowledge, methods, and capabilities for sustainable use and management of the Earth's subsurface, including assessment of linkages to water, environment, energy infrastructure and society.

EESA PROGRAMS

**and select Program Domains*

While people reside in Departments, projects and initiatives reside in Programs, which are often aligned with specific sponsors

ATMOSPHERIC SYSTEMS RESEARCH

Margaret S. Torn *mstorn@lbl.gov*

The Atmospheric Systems Research program seeks to improve understanding of surface atmosphere exchanges of carbon, water, and energy, and their roles in ecosystem-climate interactions, as well as to quantify the convective transport of CO_2, water, mass, and momentum.

BASIC ENERGY SCIENCES (BES) GEOCHEMISTRY

Benjamin Gilbert *bgilbert@lbl.gov*

The Basic Energy Sciences Geochemistry program studies the fundamental chemical controls on the structure, properties and evolution of rock-fluid systems in Earth's terrestrial and subsurface settings.

BASIC ENERGY SCIENCES (BES) GEOPHYSICS

Steven R. Pride *srpride@lbl.gov*

The Basic Energy Sciences Geophysics program conducts research on the impact of fluids injected into the subsurface, which is essential for a host of activities that require an improved ability to monitor and image in space and time where injected fluids migrate and what alterations they make to the Earth's subsurface.

BASIC ENERGY SCIENCES (BES) ISOTOPE

Donald J. DePaolo *djdepaolo@lbl.gov*

The Basic Energy Sciences Isotope program develops and applies knowledge of stable isotope fractionation processes to provide insights into the controls on mineral precipitation and material transport in fluid phases.

BIOENERGY

Harry R. Beller *hrbeller@lbl.gov*

The Bioenergy program's research includes synthetic biology, bioengineering, and microbiology to foster renewable fuel production, with key themes in developing novel biofuel pathways in bacteria; exploiting microbial metabolic diversity for biofuel production and lignocellulose deconstruction; and mitigating petroleum souring.

CLIMATE MODELING

Travis A. O'Brien *taobrien@lbl.gov*

The Climate Modeling program develops global process-resolving models to help quantify the complex and critical roles of climate feedbacks and interactions in climate change, including abrupt and extreme climate changes from anthropogenic warming, which pose great risks to society and the environment.

*EARTH SYSTEMS AND SOCIETY

Andy Jones *adjones@lbl.gov*

The Earth Systems and Society program provides decision-relevant insight about processes at the interface of human and natural systems to support resiliency of energy, water, agriculture, and built environments in the face of global and regional change.

ECOSYSTEMS BIOLOGY

Eoin Brodie *elbrodie@lbl.gov*

The Ecosystems Biology program focuses on discovering and understanding the molecular basis of plant, microbial and metazoan interactions, including specific gene functions, interactions, and community dynamics under a variety of environmental conditions-and developing the advanced technology to enable such understanding.

ENVIRONMENTAL REMEDIATION AND WATER RESOURCES

Kenneth H. Williams *khwilliams@lbl.gov*

The Environmental Remediation and Water Resources program goal is to improve the scientific foundation of hydrological, biological, and geochemical processes and their interactions relevant to environmental remediation, water resources, and enhanced energy production.

GEOLOGIC CARBON SEQUESTRATION

Curt Oldenburg *cmoldenburg@lbl.gov*

The Geological Carbon Sequestration program uses theory along with lab, field, and simulation approaches to investigate processes needed to inform and guide the safe and effective implementation of geologic carbon sequestration.

GEOTHERMAL SYSTEMS

Patrick F. Dobson *pfdobson@lbl.gov*

The Geothermal Systems program is focused on developing innovative technologies for identifying and characterizing conventional and hidden natural hydrothermal systems; and characterizing, developing, and sustaining enhanced geothermal systems, through the use of coupled process models, monitoring, and laboratory studies.

HYDROCARBON RESOURCES

Tim Kneafsey *tjkneafsey@lbl.gov*

The Hydrocarbon Resources program focuses on developing an understanding of the basic concepts and processes governing the storage and nonisothermal flow of hydrocarbons in conventional and unconventional reservoirs, as well as an understanding of associated coupled processes and phenomena involved in resource development and production.

NUCLEAR ENERGY AND WASTE

Jens Birkholzer *jtbirkholzer@lbl.gov*

The Nuclear Energy and Waste program performs fundamental and applied Earth sciences research concerning the safe, secure, and responsible use of nuclear energy, as well as the safe storage and disposal of used nuclear fuel and waste.

NANOSCALE CONTROLS ON GEOLOGIC CO_2

Donald J. DePaolo *djdepaolo@lbl.gov*

The Nanoscale Control of Geologic CO_2 program enhances the performance and predictability of subsurface storage systems by understanding the molecular and nanoscale origins of CO_2 trapping processes, and developing computational tools to translate to larger-scale systems.

*RESILIENT ENERGY, WATER AND INFRASTRUCTURE

Peter Nico *psnico@lbl.gov*

The Sustainable Energy Systems program develops and applies scientific approaches to solving existing and emerging challenges of sustainability and resiliency of subsurface energy use that are important for water-energy, critical infrastructure, risk analysis and grid-scale energy storage.

TERRESTRIAL ECOSYSTEM SCIENCE

Margaret S. Torn *mstorn@lbl.gov*

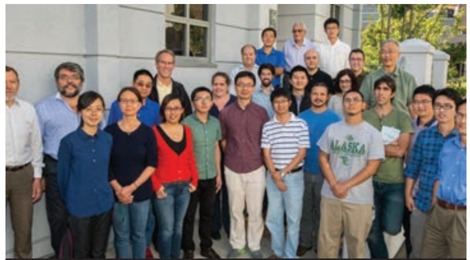
The Terrestrial Ecosystem Science program goal is to understand and explain mechanisms and processes controlling primary production, carbon cycling, and soil biogeochemistry; the impacts of disturbance on terrestrial ecosystems; ecosystem feedbacks to climate in vulnerable environments; and establishing and maintaining environmental field observatories to conduct this research.

EESA DEPARTMENTS & CORE CAPABILITIES

Each EESA scientific staff member is affiliated with one of five Departments, which represent disciplinary strengths. Departments are matrixed across the two Divisions. Scientists from different Departments work together on a range of complex challenges and transfer insights across Divisions and Programs.

EESA OPERATIONS

The EESA Operations team provides a strong foundation for enabling our scientists and research staff to carry out their short and long-term research objectives. Select operations activities include facilities, EH&S, finance and business management; project management; scientific writing, graphics and communication; administrative support; and the implementation of new collaboration tools for advancing EESA's scientific mission.



1 / HYDROGEOLOGY

Barry Freifeld *bmfreifeld@lbl.gov*

Scientists in the Hydrogeology Department advance theoretical, experimental, field, and modeling approaches to better understand subsurface fluid processes relevant to a range of energy and environmental applications.

CORE CAPABILITIES

ADVANCED PROCESS MODELING
quantitative understanding for controlling physical and chemical processes in geologic systems and prediction of subsurface fluid resource recovery, storage and protection.

CONTAMINANT HYDROLOGY
subsurface contaminant characterization and remediation using laboratory experiments, numerical modeling and field tests.

RESERVOIR ENGINEERING
enhanced production of energy from subsurface reservoirs, including from methane gas hydrate, geothermal, and oil and gas resources requiring multiphase flow modelling and petroleum fluid mechanics.

VADOSE-ZONE AND FRACTURED MEDIA
characterization and prediction of flow and transport in fractured and unsaturated systems. laboratory and theoretical studies in interfacial, wetting, and capillary phenomena as well as fracture genesis and propagation in geologic materials.

COUPLED PROCESSES
coupling of complex non-isothermal, geochemical, and geomechanical process understanding gained through an integrated experimental, monitoring and modeling analysis that combines laboratory experiments and *in situ* tests.

FIELD STUDIES AND ADVANCED MONITORING TECHNOLOGIES
expertise in carrying out field studies using airborne, surface and subsurface technologies, and integrating fluid sampling, pressure, temperature, and fiber-optic sensors for well-based monitoring.

IMAGING AND PORE SCALE PROCESSES
using X-ray CT, synchrotron light and other imaging techniques investigate geologic materials and processes from pore scale to core scale.

2 / GEOPHYSICS

Tom Daley *tmdaley@lbl.gov*

Scientists in the Geophysics Department develop cutting-edge approaches to characterize subsurface properties and processes using geophysical and geomechanical datasets together with other datasets.

CORE CAPABILITIES

ADVANCED GEOPHYSICAL INSTRUMENTATION
innovative geophysical hardware and methods for subsurface imaging and monitoring, including tomographic, micro-earthquake, and fiber-based monitoring systems.

ENVIRONMENTAL GEOPHYSICS
stochastic integration of geophysical and other datasets to estimate hydrological and biogeochemical properties of the critical zone and deeper reservoirs.

GEOMECHANICS
quantification of elastic and poroelastic response of earth materials, typically in a setting that involves fluids such as water, CO_2 or oil stored in Earth reservoirs, and assessment of potential damage such as induced seismicity.

GEOPHYSICAL COMPUTATION FOR MODELING AND IMAGING
novel inversion of geophysical datasets using high performance computing for estimation of rock properties including fracture orientation, fracture density, pressure, temperature, permeability and fluid saturations.

ROCK PHYSICS AND COUPLED DYNAMICS
experimental analysis and theory to understand relationships between geophysical attributes (such as seismic velocity, seismic attenuation, and electrical conductivity) and rock properties (such as porosity, permeability, and fluid saturation).

SOLIDS AND STRUCTURES
high performance simulation, experimental and sensing approaches to understand how strong ground motion influences the dynamic response of critical infrastructure.

3 / GEOCHEMISTRY

Carl Steefel *cisteefel@lbl.gov*

Scientists in the Geochemistry Department develop new methods and models to quantify and predict interactions between fluids, minerals and microbes that occur over a range of scales and geochemical gradients.

CORE CAPABILITIES

BIOGEOCHEMICAL CYCLING
quantification of biogeochemical cycles of carbon, metal, and other nutrients in natural environments using field and laboratory experiments.

ENVIRONMENTAL GEOCHEMISTRY
use of analytical and synchrotron-based spectromicroscopic techniques to unravel the low temperature chemical and physical heterogeneity of natural samples and to quantify associated reactions and rates.

HIGH TEMPERATURE GEOCHEMISTRY
use of hydrothermal reactors to quantify geochemical properties and transformations at temperatures up to 400°C and pressures up to 200MPa.

ISOTOPE GEOCHEMISTRY
development of isotopic ratio methods to quantify past and current mineral-fluid interactions and rates through use of the Center for Isotope Geochemistry (CIG).

MOLECULAR AND NANOGEOCHEMISTRY
quantification of fundamental, molecular-scale phenomena that underpin natural biogeochemical processes, including the properties and environmental roles of natural nanoparticles.

REACTIVE TRANSPORT MODELING
pore through watershed scale approaches to simulate coupled mineral-water-gas reactive transport in heterogeneous geologic materials, often using high performance computing.

4 / ECOLOGY

Romy Chakraborty *rchakraborty@lbl.gov*

Scientists in the Ecology Department develop new approaches to interrogate and simulate biological processes important for environmental health and sustainable energy.

CORE CAPABILITIES

BIOLOGICAL TECHNOLOGIES
development of novel approaches for characterizing plant, microbial and metazoan diversity, physiology and biochemistry, including technologies to rapidly profile the composition and function of microbial populations, image living cells, access metabolic potential, and quantify contributions to key biogeochemical processes.

SYNTHETIC BIOLOGY
discovery of novel pathways including those related to organic matter depolymerization, biosynthesis of fuels, and transformation of critical materials, and the heterologous expression or re-engineering of these pathways in bacteria and other organisms.

ENVIRONMENTAL MICROBIOLOGY
quantification of metabolic functioning of microorganisms that mediate environmental processes, with a focus on both cultivation and systems biology based approaches to determine the molecular basis of key traits of microorganisms that mediate the Earth's biogeochemical cycles.

TRAIT-BASED MODELING OF MICROBIAL COMMUNITIES
development of numerical models that represent the dynamic feedbacks between complex microbial communities and their environment or host, with a particular emphasis on the integration of information from microbial physiology, multi-omics, imaging and isotope systematics to inform model structure and parameter estimates.

5 / CLIMATE SCIENCES

Sebastien Biraud *scbiraud@lbl.gov*

The Climate Sciences Department focuses on measuring and simulating watershed, ecosystem and atmospheric processes and their interactions.

CORE CAPABILITIES

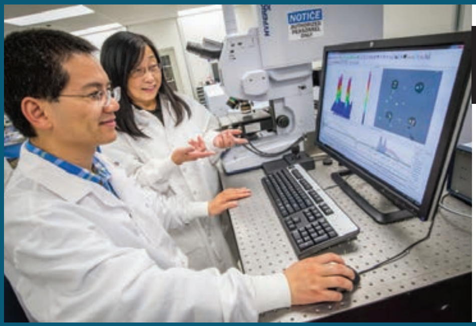
MEASURING AND MODELING THE TERRESTRIAL CARBON CYCLE
field observations and ecosystem manipulation experiments to study soil biogeochemistry, vegetation dynamics, and tropical, boreal, and sub-Arctic ecology, yielding interpretation of eddy covariance measurements, tower and aircraft observations, and isotopic measurements of CO_2, CH_4, CO, ^{13}C, and ^{18}O.

MODELING CLIMATE CHANGE AND CLIMATE CHANGE SOLUTIONS
advances multiscale simulations of abrupt and extreme climate change through development, deployment, and diagnosis of new predictive model frameworks, which includes the first global climate models based on adaptive-mesh refinement techniques to study localized climate phenomena (such as land ice-sheet evolution and hurricane formation), and expertise to analyze simulations of climate and resource supply and demand to identify promising pathways for climate-change mitigation.

SIMULATING CLOUDS, RAIN, AND THE WATER CYCLE
offers expertise in cloud and convective dynamics and the ability to incorporate that knowledge into Earth System Models to study the energy available for triggering convection and its coupling with the large-scale environment, and the transport of mass, momentum, aerosols, water vapor, and other chemical species in convection.

EESA RESEARCH FACILITIES

EESA and its divisions develop and maintain world-class instrumentation and analytical and computational facilities that support our research mission. Several of these facilities are world-unique, and are also available for use by collaborators, Berkeley scientists, and visiting researchers.

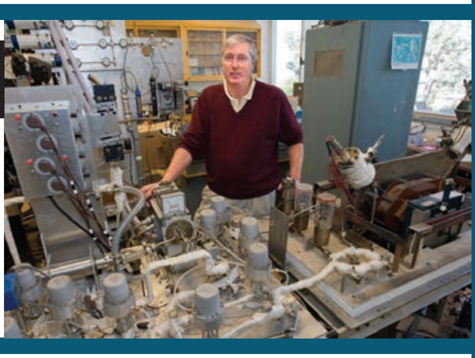


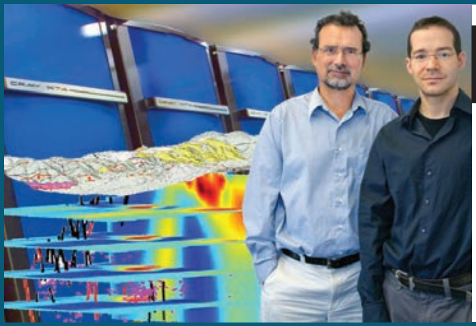
BERKELEY LAB SYNCHROTRON INFRARED STRUCTURAL BIOLOGY PROGRAM

The Berkeley Lab Synchrotron Infrared Structural Biology Program is uniquely located on the roof blocks of the Advanced Light Source linear accelerator and beamline test facility. It has the capability to advance the imaging of living microbes. Adjacent to the Fourier transform infrared microscopes are biological equipment necessary to grow and prepare living specimens.

CENTER FOR ISOTOPE GEOCHEMISTRY

The Center for Isotope Geochemistry is located across Berkeley Lab and UC Berkeley and includes a support staff of roughly 25 experts. This state-of-the-art analytical facility was established in 1988 to measure the concentrations and isotopic compositions of elements in rocks, minerals, and fluids in Earth's crust, atmosphere, and oceans.





CENTER FOR COMPUTATIONAL GEOSCIENCE

The Center for Computational Geoscience maintains a state-of-the-art computing environment that supports various geophysical research programs, such as the development of new methods for imaging the subsurface and its processes, and methods for visualizing results.

GEOSCIENCES MEASUREMENT FACILITY (GMF)

The Geosciences Measurement Facility is designed and maintained to support a wide range of Earth and Environmental Science projects. This facility focuses on the development of novel instrumentation and on scaling those systems for field deployments. With its own prototyping machine shop, dedicated lab space and technical areas, over 300 geophysical, hydrological and geochemical instruments and a staff of six, GMF is a unique facility across the DOE complex.and a staff of 6, GMF is a unique facility across the DOE complex.

ROCK DYNAMICS AND IMAGING LABORATORY

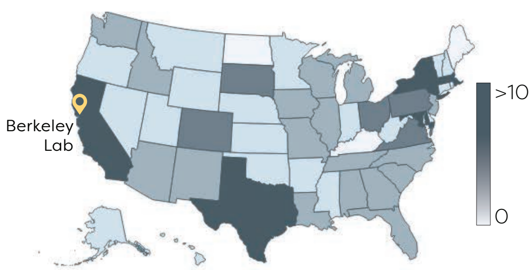
The Rock Dynamics and Imaging Lab has capabilities to make measurements on rock, fractured rock, and soil samples over a wide range of temperature and pressure conditions needed to understand mechanical and hydrologic processes. Many studies can also be performed with concurrent X-ray computed tomography (CT) imaging, allowing a means of process visualization, as well as process quantification.

EESA BY THE NUMBERS

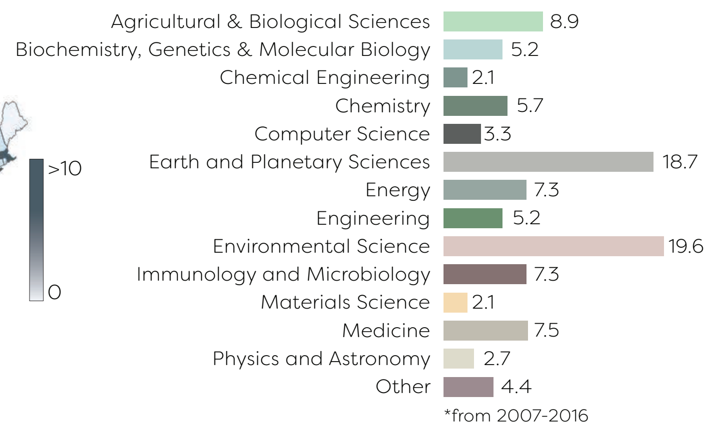
The Earth & Environmental Sciences Area partners widely with universities, industries, and other National Laboratories across the United States and the globe.

International Partnerships

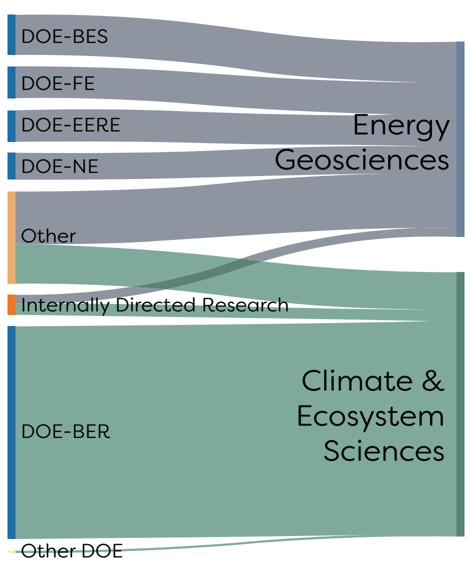
Domestic Partnerships



Publications by Discipline* (%)

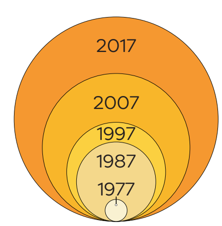


EESA FY16 Division Funding by Sponsor

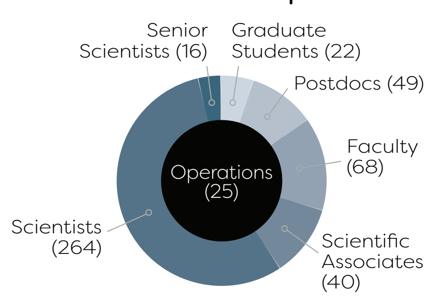


DOE: Department of Energy | BER: Biological and Environmental Research
BES: Basic Energy Sciences | FE: Fossil Energy | NE: Nuclear Energy

EESA Funding Growth by Decade



EESA Staff Composition



GLOSSARY OF EARTH AND ENVIRONMENTAL SCIENCE TERMS

abiotic/biotic - abiotic factors are the nonliving physical and chemical components of an ecosystem, and biotic factors are the living components of an ecosystem

adaptive control - the iterative process of manipulating inputs or variables, observing the effect, and using feedback to control the next iteration of the cycle

adaptive-mesh refinement - allows models to 'telescope' into compartments of a system to change resolution where and when needed to improve prediction of larger system functioning

anthropogenic - caused or influenced by human activity

bedrock-to-canopy - from the layer of rock beneath soil layers to the top of vegetation

bioenergy - renewable energy made available from materials derived from biological sources

biogeochemistry - the study of the chemical, physical, geological, and biological processes and reactions that govern the composition of the natural environment

biosphere - the global ecological system integrating all living organisms and their relationships

capillary fringe - the region just above the water table that is nearly saturated due to the combined influences of mineral wetting and surface tension

carbon sequestration - a process by which carbon is removed from the atmosphere and stored in the subsurface

carbon sink - The function provided by terrestrial ecosystems, such as prairies and forests, that store carbon (including from greenhouse gas emissions) as plant biomass and organic materials in soil

detritusphere - the region impacted by non-living organic matter

Earth system - the interacting physical, chemical, and biological processes in Earth's land, oceans, atmosphere and poles, including the natural water, carbon, nitrogen, phosphorus and other cycles, as well as all forms of life. In many cases, humans are now the main drivers of change in the Earth system.

eco-technologies - a class of technologies that include living ecosystems as part of the method for solving a problem

ecological succession - the process of change in the structure of an ecological community over time

ecotones - regions of transition between two biological communities

endophytes - organisms, often fungi and bacteria, that live between living plant cells

evapotranspiration - the process by which water is transferred from the land and plants to the atmosphere

exascale computing - supercomputing systems capable of performing at least 10^{18} calculations per second

genome-to-watershed - the scale over which hydrological perturbations and biogeochemical cycles can have an impact on downgradient water discharge and quality

groundwater banking - using excess rainwater and snowmelt to infiltrate water into aquifers deep underground where it can be stored and redrawn

hyporheic zone - the region where groundwater and surface water interact

in situ - in its original place

lithology - the description of physical characteristics of a rock sample, such as colour, texture, grain size, or composition

mechanistic models - describe a complex system by examining the workings of its individual parts and the manner in which they are coupled

meso-scales - an intermediate scale linking smaller- and larger-scale phenomenon

metabolic diversity - in the context of microbes, the means by which a microbe obtains the energy and nutrients it needs to live and reproduce

metazoan - a major group of multi-cellular eukaryotic organisms capable of locomotion, responsive to their environment, and that feed by consuming other organisms

microbes - a very diverse class of organisms found in all components of the biosphere that include all bacteria, archaea and most protozoa, as well as some species of fungi and algae

microbiome - the combined genetic material of the microorganisms in a particular environment

mineral weathering - the breakdown of rocks and minerals through physical, chemical and biological processes

nanoporous - materials that consist of a regular organic or inorganic framework supporting a regular, porous structure on the order of 100 nanometers or smaller

nutrient fixation - the process by which atmospheric compounds such as nitrogen and phosphorous are assimilated into organic compounds, especially by microorganisms

permafrost - subsurface regions that have been frozen for two or more consecutive years

remote sensing - the acquisition of data without the use of physical contact with the subject of interest

resilience - the ability to anticipate, prepare for, and adapt to changing conditions and withstand, respond to, and recover rapidly from disruptions

rhizosphere - the narrow region of soil directly influenced by living roots

scale-adaptive modeling - the ability to change simulation mesh size to simulate variable scale phenomena

soil aggregate - soil particles that bind to each other more strongly than to adjacent particles and where the space between aggregates provides retention and exchange of air and water

soil foodweb - the community of organisms living all or part of their lives in the soil

stochastic - having a random probability distribution or pattern that may be analyzed statistically but may not be predicted precisely

summit-to-seas - encompassing the terrestrial region from mountain tops to the coastline

sustainability - the capacity and ability to satisfy needs in one arena without overly inhibiting the current or future functioning of another

telemetry networks - an integrative trans-disciplinary field that promotes actionable research towards the maintenance or enhancement of ecosystem services

translational ecology - an integrative trans-disciplinary field that promotes actionable research towards the maintenance or enhancement of ecosystem services

trophic level - each of several hierarchical levels in an ecosystem, comprising organisms that share the same function in the food chain and the same nutritional relationship to the primary sources of energy

vadose zone - a variably saturated subsurface region between the ground surface and the water table

watershed - an area of land where all water that falls in and drains off of it flows to a common outlet

LIST OF FIGURES

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